Horticulture Innovation Australia

Final Report

Weed Management for the Vegetable Industry - Scoping Study

Dr Paul Kristiansen
University of New England

Project Number: VG13079

VG13079

This project has been funded by Horticulture Innovation Australia Limited using the vegetable industry levy and funds from the Australian Government.

ISBN 0 7341 3601 3

Published and distributed by:
Horticulture Innovation Australia Limited
Level 8, 1 Chifley Square
Sydney NSW 2000
Tel: (02) 8295 2300
Fax: (02) 8295 2399

HAL Project No. VG13079

6th August 2014

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Mr Michael Coleman, Ms Christine Fyfe, Professor Brian Sindel (University of New England). This scoping study was prepared for Horticulture Australia Limited by the University of New England to identify weed management issues in vegetable crops, including problematic weeds, current best practices, extension needs, and future R&D options for sustainable weed management.

Disclaimer

This report contains survey results and opinions regarding herbicide use and weed management practices during the course of this project. Please refer to the APVMA website for the most current information on pesticide permits and registrations http://apvma.gov.au/.

Acknowledgements

This project has been funded by HAL using the vegetable industry levy and matched funds from the Australian Government.

We greatly appreciate the input of vegetable farmers from across Australia, including those who completed our survey, spoke to us on the phone, attended a regional focus group meeting, and particularly those who welcomed us to their farm to conduct an interview.

We are grateful to each of our regional contacts, who gave their time so generously to arrange and take part in the field trips in each district, while also helping to arrange follow up telephone interviews: Michael Sippel (Lockyer Valley Growers, Qld); Phil Frost (Peracto, Tas); Simon Nowell (Elders, Tas); Stephen Moore (EE Muir and Sons, Vic); Sarah Houston (VegetablesWA); Tony Burfield (private consultant, SA); Greg Owens (NT Farmers); and Leigh James (Greater Sydney LLS, NSW).

We thank representatives from AgNova, Bayer CropScience, Crop Care Australasia, Dow AgroSciences, Dupont, Nufarm, Serve-Ag, Syngenta, BASF and Sumitomo for their assistance with our herbicide survey. We are grateful for the assistance of AUSVEG (Tim Shue) in distributing our survey to farmers.

Finally, we thank the following HAL staff for their assistance: Ben Callaghan, Byron de Kock, Will Gordon, Melanie Davies, Jodie Pedrana and Angus Street.

Table of Contents

List of Tables iv

List of Figures v

Media Summary 1

Technical Summary 2

1. Introduction 4
- **1.1. Background** 4
- **1.2. Objectives** 5
- **1.3. Report structure** 5

2. Methodology 6
- **2.1. Literature review** 6
- **2.2. Industry consultation** 7
  - 2.2.1. Recruitment 7
  - 2.2.2. National survey 8
  - 2.2.3. Regional focus group meetings 8
  - 2.2.4. Regional farm visits 9
  - 2.2.5. Key informant interviews 14
  - 2.2.6. Herbicide availability survey 14
- **2.3. Data synthesis and reporting** 15

3. Weeds and their impact 17
- **3.1. Weeds reported in Australian vegetable crops** 17
- **3.2. Most common weeds and their impact** 21
  - 3.2.1. Fat hen (Chenopodium album) 23
  - 3.2.2. Nutgrass (Cyperus rotundus) 24
- **3.3. Other notable weeds and their impact** 27

4. Current weed control methods 29
- **4.1. Chemical controls** 31
  - 4.1.1. Current registered herbicides in Australia 31
  - 4.1.2. Minor use permits 31
  - 4.1.3. Pre-emergent herbicide application 31
  - 4.1.4. Post-emergent herbicide application 34
  - 4.1.5. Fallow herbicide application 35
  - 4.1.6. Shielded inter-row herbicide application 37
  - 4.1.7. Spot-spray herbicide application 39
  - 4.1.8. Fumigation 39
  - 4.1.9. Bioherbicides 40
- **4.2. Mechanical weed control** 40
  - 4.2.1. Chipping and hand weeding 40
  - 4.2.2. Tillage during fallow and before sowing or planting 42
  - 4.2.3. Inter-row tillage 44
  - 4.2.4. Intra-row tillage 45
- **4.3. Mulches** 47
  - 4.3.1. Plastic mulch 47
  - 4.3.2. Biodegradable mulch 49
  - 4.3.3. Organic mulch 52
- **4.4. Other weed control methods** 52
  - 4.4.1. Solarization 52
  - 4.4.2. Thermal weed control 53

4.4.3. Green manure crops ... 54
4.4.4. Biofumigation ... 56
4.4.5. Crop rotation ... 57
4.4.6. Increased plant density ... 58
4.4.7. Farm hygiene ... 60
4.4.8. Permanent beds and controlled traffic farming ... 63
4.4.9. Precision agriculture ... 64
4.4.10. Weed sensor technology ... 64
4.4.11. Stale and false seedbeds ... 65
4.4.12. Irrigation management ... 67
4.4.13. Grazing and slashing ... 67
4.4.14. Vertebrate pest control ... 68
4.5. Features of an integrated weed management approach ... 68
4.6. Critical factors for weed control success ... 70
4.6.1. Weed control methods ... 70
4.6.2. Timing ... 70
4.6.3. Diligence ... 71
4.6.4. Knowledge and planning ... 71
4.6.5. Integrated weed management ... 72

5. Research and development ... 73
5.1. Chemical control research ... 73
5.1.1. Gaps in herbicide availability ... 73
5.1.2. New herbicides ... 76
5.1.3. Herbicide registration ... 80
5.1.4. Minor use permits ... 81
5.1.5. Herbicide resistance ... 82
5.1.6. Correct herbicide usage and fine tuning ... 83
5.2. Non-chemical control research ... 84
5.2.1. Tillage ... 84
5.2.2. Biodegradable mulch film ... 84
5.2.3. Green manures and cover crop mulches ... 85
5.2.4. Biofumigation ... 85
5.2.5. Chipping and hand weeding ... 86
5.2.6. Crop rotation ... 86
5.2.7. Permanent beds, controlled traffic farming and precision agriculture ... 87
5.2.8. Thermal weed control ... 88
5.2.9. Solarization ... 88
5.2.10. Stale and false seedbeds ... 89
5.2.11. Weed seed bank ... 89
5.2.12. Biological control ... 89
5.2.13. Genetic modification ... 90
5.2.14. Irrigation management ... 91
5.2.15. Harvest, post-harvest and fallow management ... 93
5.3. Improving weed management efficiency ... 94
5.3.1. Integrated weed management ... 94
5.3.2. Decision support ... 94
5.4. Management of specific weed species ... 95
5.5. Weed management in specific crops ... 95
5.5.1. Brassicas ... 95
5.5.2. Leafy vegetables ... 96
5.5.3. Cucurbits ... 97
5.6. Weed management in specific regions of Australia ... 97
5.6.1. The Top End ... 97

5.6.2. Peri-urban regions of Sydney and Melbourne 98
5.7. Environmental impact and soil health 98
5.8. Economic impact 99
5.9. Using existing research findings 100
5.10. Linking weeds with other crop pests 100

6. Extension 102
6.1. Sources 102
6.1.1. Personal information sources 104
6.1.2. Written information sources 107
6.1.3. Online information sources 107
6.2. Information needs 108
6.2.1. Weed species 108
6.2.2. Weed impact 109
6.2.3. Chemical control 109
6.2.4. Current and innovative weed control methods 111
6.2.5. Integrated weed management 112
6.2.6. Region-specific information 112

7. Research, Development and Extension Plan 113
7.1. Approach 113
7.2. Research and Development Plan 114
7.2.1. Introduction 114
7.2.2. Research and Development Priorities 114
7.3. Extension Plan 121
7.3.1. Introduction 121
7.3.2. Extension Priorities 121

References 125

Attachment 1: Current Weed Management Chemicals 129

List of Tables

Table 2.1 Focus group meeting locations and number of attendees 9

Table 2.2 Farm visit locations and number of farm visits per region 10

Table 3.1 Weeds in Australian vegetable crops, sorted by number of identifications during industry consultation 18

Table 4.1 Mean **effectiveness** of weed control methods (national survey respondents, where 1 = 'Not Effective' and 5 = 'Highly Effective') 30

Table 4.2 Mean **affordability** of weed control methods (national survey respondents, where 1 = 'Not Affordable' and 5 = 'Highly Affordable) 30

Table 5.1 Potential herbicide options for Australian vegetable production 77

Table 6.1 Sources of information for the Australian vegetable industry, sorted by number of identifications during industry consultation (n = 65) 103

Table 6.2 Most trusted sources of information for the Australian vegetable industry, sorted by number of indications during industry consultation (multiple response)... 104

Table 7.1 Research and Development Themes 118

Table 7.2 Extension Themes 123

Table A1 Herbicides currently registered for use in Australian vegetable crops 129

Table A2 Minor use herbicide permits for Australian vegetable crops, June 2014 135

List of Figures

Figure 2.1 Focus group meeting in Katherine, NT. 9

Figure 2.2 Carrot crop near Gatton, Qld. 11

Figure 2.3 Cut leaf vegetable farm near Richmond, Tas. 11

Figure 2.4 Recently harvested fennel crop in Werribee South, Vic. 12

Figure 2.5 New leafy vegetable crop near Gingin, WA. 12

Figure 2.6 Mixed vegetable farm near Currency Creek, SA. 13

Figure 2.7 Cucurbit farm east of Darwin, NT. 13

Figure 2.8 Mixed vegetable farm south of Richmond, NSW. 14

Figure 3.1 Count of distinct weed species identified during industry consultation, classified by perenniality: short (annual and/or biennial), either (variable or uncertain perenniality), or long (perennial); and weed type: broadleaf or grass/sedge (n = 83). 21

Figure 3.2 Capeweed (Artotheca calendula) was found to be a problem in lettuce crops in WA. 22

Figure 3.3 Fan hen (Chenopodium album) on a farm near Gatton, Qld. 23

Figure 3.4 Nutgrass (Cyperus rotundus) plant parts, plant removed from a lettuce crop near Gingin, WA. 25

Figure 3.5 Nutgrass piercing plastic mulch in a cucurbit crop near Bundaberg, Qld (Source: Sindel et al. 2011). 25

Figure 3.6 London rocket (Sisymbrium irio) on a farm near Gatton, Qld – an example of a weed with a significant local impact. 28

Figure 4.1 Applying pendimethalin (Stomp) pre-plant to lettuce beds near Gatton, Qld. Pendimethalin is an effective and commonly used pre-emergent herbicide, but can stunt lettuce crop growth under certain conditions (Qld DAFF 2010). 32

Figure 4.2 Fallow paddocks such as this one near Darwin, NT, can be an important weed refuges if careful fallow management (such as herbicide application) is not undertaken. 36

Figure 4.3 Shielded inter-row herbicide unit, Bundaberg Qld (source: Sindel et al. 2011) 37

Figure 4.4 Irrigation lines controlled for weeds with shielded non-selective herbicide application, near Adelaide, SA. 38

Figure 4.5 Chipping in an organic cucurbit crop in NT. 41

Figure 4.6 An illustration of the stages of crop bed forming near Werribee South, Vic... 43

Figure 4.7 Scuffler used for inter-row tillage in Gatton, Qld........ 44

Figure 4.8 Tillage used within a lettuce crop bed near Gingin, WA........ 45

Figure 4.9 Weedfix cultivator used for intra-row tillage near Adelaide, SA. 46

Figure 4.10 Plastic mulch used on a cucurbit crop near Katherine, NT. 48

Figure 4.11 Biodegradable mulch film during the breakdown phase near Childers, Qld (Source: M Everett, Research Agronomist, Valencia Ecosystems). 51

Figure 4.12 Plastic mulch roller for applying mulch film, near Darwin, NT. 51

Figure 4.13 Barley used as a green manure crop on a vegetable farm near Currency Creek, SA. 54

Figure 4.14 Green manure crop 'crimping roller', being trialled on an organic vegetable farm near Gatton, Qld, to provide a cover crop 'killed mulch'. 56

Figure 4.15 Lettuce planting near Gatton, Qld. An ideal planting density will provide some competition with weeds in the crop beds, while at the same time not forcing crop plants to compete with each other for resources........ 59

Figure 4.16 Vehicle washdown near Richmond, Tas........ 61

Figure 4.17 Vehicle washdown bay near Gingin WA........ 61

Figure 4.18 Biosecurity sign near Gingin, WA........ 62

Figure 4.19 Slashing is more commonly used by organic vegetable farmers to manage weeds in areas such as headlands, non-cropping areas and irrigation lines, such as the kikuyu growing in the irrigation lines of this organic farm near Adelaide, SA. 68

Figure 5.1 Calligrapha pantera, released in NT as a biological control of the weed Sida acuta. 91

Figure 5.2 Sophisticated overhead irrigation near Gingin, WA........ 92

Figure 5.3 Spray irrigation near Werribee, Vic. 92

Figure 5.4 A farmer near Richmond, NSW, was experimenting with trickle irrigation to limit the moisture available for weed growth in between the crop rows. 93

Figure 5.5 Wild radish is an important weed of brassica crops, and is hard to manage due to its similarities to these crop species. 96

Figure 5.6 Weedy non-cropping areas, such as this storage dam bank near Werribee, Vic, may be important refuges for crop pests, viruses and diseases. 101

Media Summary

Weeds are a persistent problem for many vegetable producers in Australia. The common features of vegetable cropping systems, including frequent cultivation, irrigation, and the addition of large quantities of nutritional inputs, mean that the potential for weed growth is high. Weeds have a significant impact on crop profitability, yield and quality, and crop management.

In consultation with the Australian industry we sought to identify the most important weed species in Australian vegetable production and the methods currently used to control them, gaps in current knowledge of weed control, potential lessons from other industries, and the most important research, development and extension (RD&E) issues. The project involved a review of the literature, a national survey of vegetable farmers, focus groups and farm visits in major vegetable producing regions across Australia, and key informant interviews.

The most commonly reported weeds of Australian vegetable production were generally annual or biennial broadleaf species. Examples of common weeds were fat hen, stinging nettle, mallow, pigweed, and nutgrass. These can dominate because they seed heavily, and are more difficult to control using selective herbicides. The current strategy of most farmers to control weeds in vegetable crops includes a mixture of herbicides, cultivation, hand weeding, plastic mulch (where applicable), and crop rotation. Other methods may also be used successfully.

Nearly all farmers integrate a number of control methods ('Integrated Weed Management', IWM), because no single technique alone will effectively manage weeds in the crop during the entire growing season. However, relatively less attention has been paid to IWM in vegetables than in broadacre cropping.

The primary output of this project was a series of recommendations for weed control RD&E, to guide future investment.

Research and development priority themes	*Extension* priority themes
• new herbicide options; • biodegradable mulches; • management of specific weeds; • herbicide resistance; • weed seed bank management; • development of other weed control methods; • economic impact of weeds; • precision agriculture; and • reduced tillage	• region-specific extension; • promoting efficient herbicide use; • minor use herbicide permits; • promoting integrated weed management; and • decision support tools.

Technical Summary

Weeds are a persistent problem for many vegetable producers in Australia. The common features of vegetable cropping systems, including frequent cultivation that results in highly disturbed soil, irrigation (particularly furrow or flood irrigation), and the addition of large quantities of nutritional inputs before planting and during the growing period, mean that the potential for weed growth is high.

Weeds have a significant impact on the cost of growing a vegetable crop, as well as crop yield and quality. They make it more difficult to manage crops due to reduced pest management effectiveness, harvesting difficulties, lack of herbicide options, and limitations placed on the crop options available to farmers.

In this project, we sought to identify the most important weed species in Australian vegetable production and the methods currently used to control them, gaps in current knowledge of weed control in the industry, potential lessons from other industries, and the research, development and extension issues of most importance to the industry.

The project involved a review of the literature, a national survey of vegetable farmers, focus groups and farm visits in major vegetable producing regions across Australia, and key informant interviews.

The most commonly reported weeds of Australian vegetable production were broadleaf weeds generally of short perenniality (annual and/or biennial), although a few are annual, biennial or perennial. These weeds predominate because they seed heavily, while grass and grass-like weeds are more easily controlled using selective herbicides. Examples included fat hen (*Chenopodium* album), stinging nettle (*Urtica urens*), mallow (*Malva parviflora*), and pigweed (*Portulaca oleracea*). The sedge nutgrass (*Cyperus rotundus*) was also commonly reported, and is problematic because of its persistent underground parts.

Various weed control options are currently available to Australian vegetable farmers. These options may be categorised as 'preventive methods' (reducing weed emergence in crop beds before crop establishment), 'direct physical methods' (used directly in the crop after sowing or transplanting), and 'cultural methods' (enhancing crop competitive ability). Most are suitable at certain times of the season, or for particular management circumstances.

Commonly used weed control methods include herbicide application, tillage or cultivation, hand weeding, plastic or biodegradable mulch (depending on crop), and crop rotation. Other methods used with success by some farmers included fumigation and biofumigation, stale and false seedbeds, and farm hygiene. Nearly all Australian farmers integrate a number of these and other methods into a weed management strategy (IWM), because no single technique alone will effectively manage weeds in the crop during the entire growing season. Factors behind a successful weed control strategy include timing, diligence, and knowledge and planning.

Good progress has been made for Integrated Weed Management (IWM) in Australian broadacre grain and cotton crops in the last 20 years, however less attention has been paid to developing such weed control techniques in vegetables. This is concerning given that the grains and cotton industries have demonstrated that IWM is key to sustainable productivity.

We identified potential research issues to improve the control of weeds in vegetable crops. A key area of interest for research and development was chemical control research, including gaps in herbicide availability, new herbicide options, herbicide registration, efficiency and resistance. The limited range of herbicides available for use in vegetable crops restricts the capacity of many farmers to manage weeds, or means they must rely heavily on generally more expensive or time-consuming non-chemical approaches.

Other areas of interest in research and development included: improvement and adoption of several non-chemical control methods; weed control relating to specific weed species, crops and districts; environmental and economic impacts; the link between weeds and other pests; and decision support systems. It is suggested that using innovative approaches from other industries or overseas is an important first step to any new research and development project.

In the vegetable industry, extension is available through a variety of personal, written and online sources. All sources were useful to some farmers, however the most popular and trusted were personal information sources such as agronomists, and workshops and field days. Farmers were interested in more information on: important weed species; the impact of weeds on farm profitability; chemicals (registration details, efficient use, resistance, and environmental impacts); innovative control methods; IWM; and region-specific weed control information.

The primary output of this project was a series of recommendations for weed control research, development and extension, to guide future industry investment.

Research and development priority themes	*Extension* priority themes
• new herbicide options; • biodegradable mulches; • management of specific weeds; • herbicide resistance; • weed seed bank management; • development of other weed control methods; • economic impact of weeds; • precision agriculture; and • reduced tillage	• region-specific extension; • promoting efficient herbicide use; • minor use herbicide permits; • promoting integrated weed management; and • decision support tools.

1. Introduction

1.1. Background

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. Effective crop protection against pests and diseases is economically important for vegetable producers, and crop losses can be high if associated weeds are not controlled (Coutts & Jones 2005, Blaesing 2013). In other parts of the world, weeds have been reported to cause greater economic losses for vegetable producers than pests and diseases. And yet despite this, relatively little R&D activity has been devoted in Australia to their management, with the plant health and crop protection focus predominately on insects and diseases (Blaesing 2013).

Weed control strategies vary between crops (Henderson & Bishop 2000). For example, slow-growing or long-season species require good bed preparation and on-going attention; small leaved and low stature crops are vulnerable to fast-growing, taller weeds; and sprawling crops make accessing weeds for control activities more difficult. Closely related weeds from the same botanical families as vegetable crops are particularly troublesome.

Good progress has been made for IWM in Australian broadacre grain and cotton crops in the last 20 years (McGillion & Storrie 2006, Charles 2013). But less attention has been paid to developing such weed control techniques in vegetables, despite limited earlier studies looking at experimental herbicides, organic mulches and brassica biofumigants (VG97063 - Weed management in pumpkins and other cucurbit crops) (Henderson 2000), biodegradable mulches (Limpus *et al.* 2012) and organic weed control methods (Kristiansen *et al.* 2007). 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 only applied to organic production (Thompson 2012). This is concerning given that the grains and cotton industries have demonstrated that IWM is key to the continuing productivity of conventional farmers. In contrast, the few producers who were using “high IWM” practices expressed support for investigating new IWM practices and technologies using R&D funds, a perception shared by consultants and research/extension personnel (Thompson 2012). The report by Chivers (2012) also highlights the value of alternative weed management methods and recommends research on farming systems approaches to weed management (equivalent to IWM) and novel technologies (e.g. thermal methods).

1.2. Objectives

The research questions to be addressed by this project are as follows.

1. Which weed species are causing greatest difficulty for vegetable farmers?

2. What methods are currently being used to control weeds in vegetable crops, and with what success?

3. What knowledge and research gaps exist for weed management in the vegetable industry?

4. What lessons can be learned and applied from other agricultural industries?

5. What are the research and extension needs of vegetable producers in relation to weed management?

These questions were addressed in a literature review, a national survey of vegetable farmers, focus groups and farm visits in major vegetable producing regions across Australia, and key informant interviews. The findings from all stages of the project are summarised in this final report.

1.3. Report structure

In Chapter 2, we detail the project methodology, including each of the forms of industry consultation used, as well as data analysis and reporting. Findings from the various forms of industry consultation (literature review, farm visits, focus group meetings, and key information telephone interviews) have been aggregated in the report by topic.

Chapter 3 includes a list of all weeds reported in vegetable farms across Australia during the project, and discusses the impact of the more important weed species. In Chapter 4, we summarise the weed control methods used in Australian vegetable production, including chemical control methods, mulches, and other weed control methods.

We report on research issues and priorities identified during the consultation with industry in Chapter 5. This includes chemical and non-chemical control methods, weed management for specific crops and districts in Australia, environmental and economic impacts of weeds and their management, using existing research findings, and the link between weeds and other crop pests.

In Chapter 6, we summarise extension activity and needs within the vegetable industry, including personal, written and online information sources, and the main current information priorities of farmers and other stakeholders. Finally, in Chapter 7 a research, development and extension plan is presented, to guide future funding decisions to improve management of weeds within the Australian vegetable industry.

2. Methodology

2.1. Literature review

Weed impact and weed control issues, were explored through a review of Australian and international literature. Much of this review was is based on an earlier review of the literature completed as part of a cucurbit-specific research project (VG10048; Sindel *et al.* 2011). However, the review has been updated and expanded to include the variety of vegetable crops for this whole-industry scoping study, as well as the different research focus of this project.

Literature searches were conducted using the University of New England's library catalogue (printed publications and online documents available through several academic literature databases), the Google Scholar and Google search engines, and amongst the literature collection of the School of Environmental and Rural Science, University of New England.

The initial scope of the literature search was Australian academic literature (a key word search of relevant journals), and the search was expanded to include relevant extension publications produced by various government departments across Australia. The HAL web site was searched for relevant reports, and these acquired either from HAL or from the authors. Other relevant web sites reviewed included the Council of Australian Weed Societies (where a library of Australian Weeds Conference papers is freely available), research organisations, AUSVEG, and the Australian Bureau of Statistics. Some unpublished reports and data were acquired from their authors, while a number of horticultural experts were consulted on specific points where literature could not be found, or was insufficient. International literature was also sourced for comparative purposes, to fill gaps in the review where Australian literature could not be found, or to identify weed control techniques not yet evaluated fully in Australia.

It became evident during the course of this review that there gaps in our knowledge of some aspects of weed impact and control in vegetable crops. This is reflected in the lack of academic publications in some sections of this review, and our reliance on extension publications and international literature sources. This strongly suggests a need for further research into a number of aspects of weed ecology, impact and control within Australian vegetable crops, both in the academic field and through industry-funded research. A research, development and extension plan that offers suggestions for filling these knowledge gaps, will be included in the final report for this project.

2.2. Industry consultation

2.2.1. Recruitment

Consultation with HAL and review of the literature identified the main vegetable growing regions in each state as well as the Northern Territory, as well as identifying active grower group activity, or the presence of extension or other support staff. Grower group activity and extension was considered vital in recruiting farmers to participate in the focus group meetings, farm visits and online questionnaire.

Initial contact was made with grower group representatives and/or extension and support personnel in each potential location, to review the feasibility of farmer recruitment for the project. In many cases, the contact details for these representatives were obtained after consultation with HAL staff. These regional representatives were vital to the organisation of our farmer consultation.

This consultation and contact process resulted in the following locations being chosen for field research, along with their associated regional contacts:

- Queensland (Qld): Gatton (contact with the president and secretary of the Lockyer Valley Grower's Group).
- Tasmania (Tas): Richmond and Latrobe/Devonport (contact with the research organisation Peracto and with local agronomists).
- Victoria (Vic): Werribee (contact with a local agronomist).
- Western Australia (WA): Gingin (contact with the VegetablesWA extension officer – HAL-funded).
- South Australia (SA): Virginia, north-east Adelaide and Currency Creek (contact with a private extension professional).
- Northern Territory (NT): Darwin and Katherine (contact with the NT Farmers vegetable extension officer – HAL-funded).
- New South Wales (NSW): Richmond (contact with a NSW Local Land Services extension professional).

We acknowledge that this recruitment methods results in a selection bias towards, active, cooperative farmers, and towards regions where grower group activity was more likely. However, our previous experience (VG10048) and advice from HAL and regional contacts suggested that more independent-minded farmers were not likely to want to become involved in a research project of this nature.

However, a notable benefit of this kind of selection process is that the farmers who were recruited to the project appeared more likely to be willing to share their experiences, and willing to take any opportunity to learn from their peers. They are therefore more likely to be 'innovative' farmers who have a greater level of success in managing weeds on their farm. We therefore believe that the farmers recruited to this project provided a useful picture of weed management that all vegetable farmers may learn from.

2.2.2. National survey

An online survey nation-wide survey of vegetable farmers was conducted between late May and early July, 2014. Questionnaire design was influenced by the project goals and review of literature.

The questionnaire (Appendix 2) included questions on farm and farmer characteristics, the impact of weeds on vegetable farm operations, current weed management practices, innovations in weed management, industry research priorities, and extension sources and information requirements. We attempted to simplify the questionnaire as much as possible, while still covering all relevant project themes and questions.

The survey was conducted entirely via online questionnaire due to time constraints, using Survey Monkey (www.surveymonkey.com). The survey was promoted through the AUSVEG Weekly Update email to subscribed vegetable farmers in early June 2014, with a reminder being included in a late June Weekly Update. Additionally, we asked our regional contacts as well as other regional grower groups to advise their members of the survey's existence.

2.2.3. Regional focus group meetings

Regional visits were conducted between April and June, 2014. A regional focus group meeting was not held in Gatton on the advice of our grower group contacts in that district, due to a clash with concurrent vegetable industry events, and their belief that farmers would be unlikely to attend a meeting. We compensated for this through additional farm visits (discussed in the next section).

In the remaining regions, focus group meetings were held with vegetable farmers, agronomists and extension staff (Figure 2.1). Each focus group meeting ran for approximately two hours. Between 10 and 15 people were invited to attend each meeting about a month before they were held, with the majority of invitees being vegetable farmers. In most cases, actual attendance by vegetable farmers was lower than the number of invitees, often due to good weather on the day of our visit, which required farmers to be out in the field carrying out urgent crop activities. Despite this, we obtained rich information from the attendees of each focus group meeting, and benefited considerably from the attendance of professional agronomists at most meetings. Agronomists deal with several farmers each on a daily basis. In addition to bringing the knowledge and experiences of these farmers to the meetings, the agronomists also brought their own knowledge and professional expertise in crop management.

Two UNE staff attended each focus group meeting, one to facilitate the discussion, and another to take notes.

The number of non-UNE attendees at each focus group is summarised below in Table 2.1.

Table 2.1 Focus group meeting locations and number of attendees

Location	Attendee details
Latrobe, Tasmania	Four vegetable farmers, four agronomists and one researcher
Werribee South, Victoria	Five vegetable farmers and three agronomists
Gingin, Western Australia	Approximately ten vegetable farmers and a HAL-funded extension officer
Virginia, South Australia	One vegetable farmer, two agronomists and an extension officer
Katherine, Northern Territory	Two vegetable farmers, two agronomists, four research station staff and a HAL-funded extension officer
Richmond, New South Wales	Three vegetable farmers (one of whom was also an agronomist), an extension officer and a vegetable industry journalist

Figure 2.1 Focus group meeting in Katherine, NT.

2.2.4. Regional farm visits

While visiting each location to complete a focus group meeting, we also visited with farmers to discuss weed impact, management, research and extension in depth.

These meetings were arranged in consultation with each of our regional contacts, often with the regional contact getting in touch directly with the farmers to find out if a farm visit was possible. Where possible, we attempted to visit farmers involved in producing a variety of crops, using innovative weed management practices, or having high levels of success with weed management. As such, the visits included a mix of conventional and organic farms. An interview schedule very similar to the national survey questionnaire (Appendix 2) was used for the farm visits. Two UNE staff carried out the farm visits, mostly accompanied by our regional contact, whose presence further enriched the discussion with the farmer. The farm visits were of between one and two hours in length, and often involved a tour of the farm. Photographs were taken of crops and major weeds on each farm visited (Figure 2.2 to Figure 2.8).

As with attendees at the focus group meetings, some farmers had to cancel their appointment with us on the day of the visit due to on-farm tasks. In some places this resulted in less completed farm interviews than planned, though in some cases our regional contacts were able to identify alternative farm visits. In Latrobe Tas, alternative visits were kindly arranged on the day by one of the agronomists who attended our focus group meeting.

Table 2.2 provides details on the number of farm visits completed in each location. Additional farm visits were carried out in Gatton Qld, in lieu of a focus group meeting.

Table 2.2 Farm visit locations and number of farm visits per region

Location	Farm visit details
Queensland	Six farms visited in the Lockyer Valley near Gatton, including one organic vegetable farmer.
Tasmania	One farm visited near Richmond and two near Latrobe.
Victoria	Three farms visited in Werribee South.
Western Australia	One farm visited near Gingin.
South Australia	One farm visited in north-east Adelaide, one near Currency Creek, and one near Gawler, including two organic vegetable farmers.
Northern Territory	One farm visited south of Darwin, one east of Darwin, and one between Katherine and Pine Creek, including one organic vegetable farmer.
New South Wales	Two farms visited, one south of Richmond and one north-east of Richmond.

Figure 2.2 Carrot crop near Gatton, Qld.

Figure 2.3 Cut leaf vegetable farm near Richmond, Tas.

Figure 2.4 Recently harvested fennel crop in Werribee South, Vic.

Figure 2.5 New leafy vegetable crop near Gingin, WA.

Figure 2.6 Mixed vegetable farm near Currency Creek, SA.

Figure 2.7 Cucurbit farm east of Darwin, NT.

Figure 2.8 Mixed vegetable farm south of Richmond, NSW.

2.2.5. Key informant interviews

Key informant interviews were carried out via telephone and email to supplement the national survey and fieldwork data, allow experts from across the industry to have their say on the project, and to obtain more detailed data from vegetable growing regions not included in the focus group meetings and farm visits.

A total of nineteen interviews were completed, comprising the following:

- five vegetable farmers (NSW, NT, SA, Tas, WA);
- two agronomists (Vic, NSW);
- six government researchers (Qld, WA, Vic);
- two private researchers (SA, Tas);
- two HAL-funded extension staff (NT, WA);
- one private extension professional (SA); and
- one HAL industry services professional.

2.2.6. Herbicide availability survey

The main manufacturers and/or distributors of herbicides in Australia were identified by internet search and consultation with colleagues at the University of New England.

Company representatives were contacted by telephone and email, and asked to confirm currently registered herbicides for vegetable crops in Australia. We also asked: whether they were aware of any off-label trials that had shown potential for vegetable production; whether any currently available herbicides might be tested for their viability in vegetable production; and whether they were aware of any forthcoming products (for example, new chemistry being developed overseas) that may be useful in vegetable crops. We also posed these questions to some researchers in Australia with expertise in herbicide trial work in vegetable crops.

Contact was made with the following chemical companies:

- AgNova
- BASF
- Bayer CropScience
- Crop Care Australia
- Dow AgroScience
- Dupont
- Nufarm
- Serve-Ag
- Syngenta

Current herbicide labels for all registered products were either obtained online or provided by chemical company representatives. Data on registered vegetable crops, examples of main weeds controlled, and herbicide application timing were collated from the labels.

Minor use permit data was obtained from HAL. Data gathered included vegetable crops and weeds applicable to the permit, geographic coverage of the permit, and permit expiry date.

2.3. Data synthesis and reporting

Because a low final response of only 22 was received for the national survey, quantitative analysis of the data set has not been reported extensively in the results. The report therefore includes a synthesised discussion of the key findings from the national survey, literature review, focus group meetings, farm visits and key informant interviews. Limited quantitative findings from the national survey have been presented, though these are a guide only given that statistically significant results cannot be imputed from a small data set.

The low response to the questionnaire is disappointing, but perhaps unsurprising given our previous work with the industry (Sindel *et al.* 2011). We surmised in our previous research that a low survey response amongst vegetable farmers may be due to 'survey fatigue' in the agricultural industry, and lack of time due to farm operations. Furthermore, several of our regional contacts, extension staff and others consulted for this project suggested that having farmers complete an online questionnaire was going to be difficult. They suggested that time is a significant limiting factor for vegetable farmers, and that few of them spend enough time in front of their computer to complete an online questionnaire. Participating in research activity through an impersonal questionnaire is understandably a low priority for many vegetable farmers.

Therefore, our experience in this project strongly suggests that face to face or telephone discussion is a much better way to engage with the vegetable industry to obtain research information. We therefore recommend that future projects that engage with farmers directly adopt these approaches rather than attempting a questionnaire, either online or via the post.

3. Weeds and their impact

The common features of vegetable cropping systems, including frequent cultivation that results in highly disturbed soil, irrigation (particularly furrow or flood irrigation), and the addition of large quantities of nutritional inputs before planting and during the growing period, mean that the potential for weed growth is high. When not managed effectively, weeds can have a significant impact on productivity (Henderson and Bishop 2000).

Specific impacts of weeds within Australian vegetable cropping systems are detailed in the review of literature (Appendix 1, Section 3). Briefly, these include:

- Impact on the cost of growing a vegetable crop, due to significant weed management expenses.
- Impacts on crop yield, including weed competition with crop plants for water, soil nutrients, light and space, and damage to the crop as a direct result of weed management activities.
- Impacts on crop quality, with many weeds acting as important hosts of pests and diseases that can reduce the quality of the crop
- Various impacts on crop and farm management such as reduce pest management effectiveness, harvesting difficulties and lack of herbicide options, with the vegetable crop choices available to individual farmers possibly being limited by the presence of particular weeds.

In the following sections, we discuss the weeds identified during this project, and summarise the impacts of the most notable weeds of Australian vegetable production.

3.1. Weeds reported in Australian vegetable crops

Broadleaf and grass/sedge weeds identified in the literature review stage of this project are listed in Appendix 1, Tables 4.1 and 4.2.

Over the course of this project, we asked farmers, agronomists and researchers across Australia consulted by survey, telephone, farm visit and focus group meeting to report the most important weeds either on their farm, or in their district. This information has been compiled in Table 3.1, below. Our consultation with vegetable industry stakeholders identified 83 distinct weed species that have an impact in Australian vegetable production. A further 5 unknown species were noted by farmers and other stakeholders.

'Number of identifications' refers to the number of occasions that a weed was mentioned during industry consultation for the project. This is only a guide on how common different weeds are in vegetable production across Australia and in some districts, as a single mention at a focus group has not been weighted differently to a single mention in a survey or during a farm visit. Number of identifications is also not necessarily an indication of the overall importance of a weed species to vegetable farmers. The importance of particular weed species is discussed in the next two sections.

Table 3.1 Weeds in Australian vegetable crops, sorted by number of identifications during industry consultation

Weed botanic and common name	Number of identifications	Weed type and perenniality*	State/s present
Chenopodium album (Fat Hen)	32	broadleaf, short	NSW, Qld, SA, Tas, Vic, WA
Urtica urens (Stinging nettle)	23	broadleaf, either	NSW, Qld, SA, Tas, Vic, WA
Malva parviflora (Mallow/marshmallow)	20	broadleaf, either	NSW, Qld, SA, Tas, Vic, WA
Cyperus rotundus (Nutgrass)	19	sedge, long	NSW, NT, Qld, SA, Vic, WA
Portulaca oleracea (Pigweed/portulaca)	19	broadleaf, short	NSW, NT, Qld, Vic, WA
Amaranthus spp. (Amaranthus/Prince of Wales Feather/Redshank)	17	broadleaf, short	NSW, NT, Qld, Tas, WA
Raphanus raphanistrum (Wild radish)	17	broadleaf, short	NSW, Qld, SA, Tas, Vic, WA
Solanum nigrum (Blackberry nightshade/deadly nightshade)	17	broadleaf, either	NSW, NT, Qld, SA, Tas, Vic, WA
Sonchus oleraceus (Milk thistle/common sowthistle)	16	broadleaf, either	NSW, NT, Qld, SA, Vic, WA
Rapistrum rugosum (Wild turnip)	14	broadleaf, short	NSW, Qld, SA, Tas, Vic, WA
Polygonum aviculare (Wireweed/hogweed)	13	broadleaf, short	NSW, SA, Vic, WA
Senecio vulgaris (Common groundsel)	12	broadleaf, short	SA, Tas, Vic, WA
Stellaria media (Chickweed)	11	broadleaf, short	NSW, Qld, SA, Tas, Vic, WA
Galinsoga parviflora (Potato weed)	10	broadleaf, short	NSW, Qld, WA
Datura stramonium (Common thorn apple/Stramonium)	8	broadleaf, short	NSW, Qld, Vic
Solanum tuberosum (Volunteer potatoes)	8	broadleaf, long	NSW, Qld, SA, Tas, Vic, WA
Digitaria sanguinalis (Summer grass)	7	grass, short	Qld, Vic, WA
Grasses (Grasses misc)	7	grass, either	NSW, Qld, Tas, WA
Artotheca calendula (Capeweed)	6	broadleaf, short	SA, Tas, Vic, WA
Daucus carota (Carrot weed)	6	broadleaf, short	Qld
Fumaria spp. (Fumitory)	6	broadleaf, short	Qld, SA, Tas, Vic, WA
Lolium rigidum (Ryegrass)	6	grass, short	SA, Tas, WA
Oxalis pes-caprae (Oxalis/soursob)	5	broadleaf, long	NSW, SA, Vic
Capsella bursa-pastoris (Shepherd's purse)	4	broadleaf, short	Qld, Tas, Vic
Conyza spp (Fleabane)	4	broadleaf, short	Qld, Tas, WA
Cynodon dactylon (Couch)	4	grass, long	NSW, NT, SA, WA

** perenniality: short (annual and/or biennial), either (variable or uncertain perenniality), or long (perennial).*

Table 3.1 Continued

Weed botanic and common name	Number of identifications	Weed type and perenniality*	State/s present
Poa annua (Winter grass)	4	grass, short	SA, Vic, WA
Tribulus terrestris (Caltrop)	4	broadleaf, either	NT, SA, WA
Trifolium spp. (Clover)	4	broadleaf, either	Qld, Tas, Vic
Eleusine indica (Crab grass/crowsfoot)	3	grass, either	NT, WA
Physalis minima (Wild gooseberry)	3	broadleaf, short	NT, Qld
Sorghum halapense (Johnson grass)	3	grass, long	NSW, Qld, WA
Bidens pilosa (Cobbler's pegs/Farmer's friend)	2	broadleaf, short	NSW, Qld
Convolvulus spp. (Convolvulus)	2	broadleaf, long	Qld, Vic
Dactyloctenium radulans (Button grass)	2	grass, either	NT
Euphorbia hirta (Asthma weed)	2	broadleaf, short	NT
Galium aparine (Cleavers/bed straw)	2	broadleaf, short	SA, Tas
Ipomoea plebeia (Bell vine)	2	broadleaf, short	Qld
Oxalis latifolia (Oxalis latifolia)	2	broadleaf, long	Tas
Papaver spp. (Volunteer/wild poppies)	2	broadleaf, short	Tas
Pennisetum clandestinum (Kikuyu)	2	grass, long	SA
Pennisetum polystachion (Mission grass)	2	grass, long	NT
Polygonum convolvulus (Climbing buckwheat)	2	broadleaf, short	Qld
Senna obtusifolia (Senna/sicklepod)	2	broadleaf, either	NT
Sida acuta (Spinyhead sida)	2	broadleaf, long	NT
Trianthema portulacastrum (Black pigweed/giant pigweed)	2	broadleaf, short	Qld
Tridax procumbens (Tridax daisy)	2	broadleaf, short	NT
Acanthospermum hispidum (Goat head)	1	broadleaf, short	Qld
Acetosella vulgaris (Sorrel)	1	broadleaf, long	NT
Andropogon gayanus (Gamba grass)	1	grass, long	NT
Anthriscus caucalis (Chervil)	1	broadleaf, short	Tas
Argemone ochroleuca (Mexican poppy)	1	broadleaf, short	WA
Boerhavia dominii (Tarvine)	1	broadleaf, long	NT
Brassica napus (Wild canola)	1	broadleaf, short	NT
Brassica oleracea (Volunteer broccolini)	1	broadleaf, short	SA
Bromus spp. (Brome grass)	1	grass, either	SW
Calopogonium mucunoides (Calopo)	1	broadleaf, short	NT
Cardaria draba (Hoary cress)	1	broadleaf, long	Vic
Cenchrus echinatus (Mossman River grass)	1	grass, short	NT
Chloris gayana (Rhodes grass)	1	grass, long	NT

** perenniality: short (annual and/or biennial), either (variable or uncertain perenniality), or long (perennial).*

Table 3.1 Continued

Weed botanic and common name	Number of identifications	Weed type and perenniality*	State/s present
Coronopus didymus (Lesser swinecress)	1	broadleaf, short	Tas
Cryptostegia madagascariensis (Rubber vine)	1	broadleaf, long	NT
Cucumis myriocaropus (Paddy melon)	1	broadleaf, short	Vic
Echinochloa spp. (Barnyard grass)	1	grass, short	WA
Emex australis (Three cornered jack)	1	broadleaf, short	WA
Foeniculum vulgare (Wild fennel)	1	broadleaf, either	Vic
Hibiscus trionum (Bladder ketmia)	1	broadleaf, short	Qld
Marrubium vulgare (Horehound)	1	broadleaf, long	NT
Mitracarpus hirtus (Berrimah weed)	1	broadleaf, short	NT
Onion weed (various spp.) (Onion weed)	1	broadleaf, either	Vic
Oxalis triangularis (Purple clover)	1	broadleaf, long	Tas
Parthenium hysterophorus (Parthenium weed)	1	broadleaf, short	Qld
Salvia reflexa (Mintweed)	1	broadleaf, short	WA
Sisymbrium irio (London Rocket)	1	broadleaf, short	Qld
Sisymbrium orientale (Mustard weed)	1	broadleaf, short	SA
Solanum physalifolium (Hairy nightshade)	1	broadleaf, short	Vic
Solanum torvum (Devil's fig)	1	broadleaf, long	NT
Sonchus asper (Prickly sowthistle)	1	broadleaf, short	WA
Stachytarpheta spp. (Snakeweed)	1	broadleaf, long	NT
Typha orientalis (Bull rush (cumbungi))	1	broadleaf, long	Tas
Urochloa mosambicensis (Sabi)	1	grass, long	NT
Vicia monantha (Vetch)	1	broadleaf, short	SA
Xanthium spinosum (Bathurst burr)	1	broadleaf, short	NT

** perenniality: short (annual and/or biennial), either (variable or uncertain perenniality), or long (perennial).*

Table 3.1 suggests that the most commonly reported weeds of Australian vegetable production are broadleaf weeds, with the exception of the sedge nutgrass (*Cyperus rotundus*). These broadleaf weeds are also generally of short perenniality (annual and/or biennial), although a few are annual, biennial or perennial. Fat hen (*Chenopodium* album) stands out as the most commonly identified of this project, having been reported by project participants on 32 separate occasions. Other commonly reported weeds include stinging nettle (*Urtica urens*), mallow (*Malva parviflora*), nutgrass, and pigweed (*Portulaca oleracea*). Of the most commonly identified weeds, a number were noted in all states with the exception of NT, including fat hen, stinging nettle, mallow, and wild radish (*Raphanus raphanistrum*). The most commonly reported grass species, summer grass (*Digitaria sanguinalis*) was the seventeenth most identified weed overall, while other common grasses include ryegrass (*Lolium rigidum*) and couch (*Cynodon dactylon*).

The predominant growth habit of weeds identified was herbaceous (94%), while the remainder were either shrubs (3.6%) or vines (2.4%). The growth of plants with woody structures and seed production that is delayed for several years is disadvantaged in the regularly changing environment of intensive row cropping for vegetable production (Baker 1974).

A summary of the characteristics of perenniality and type (broadleaf or grass) of the weeds reported during this project is presented in Figure 3.1. Of the 83 weeds identified, 79.5% were broadleaf weeds, and the remaining 20.5% were either grasses or sedges. Broadleaf weeds predominate because grass and grass-like weeds are more easily controlled using selective herbicides. Short-lived (annual and/or biennial) broadleaf weeds were the most common category, comprising approximately 50% of all species identified during the project. As has already been noted, many of the most commonly reported weeds were also short-living perennial species (Table 3.1). Common weeds of vegetable production, and some of their main impacts, are each discussed in more detail in Section 3.2.

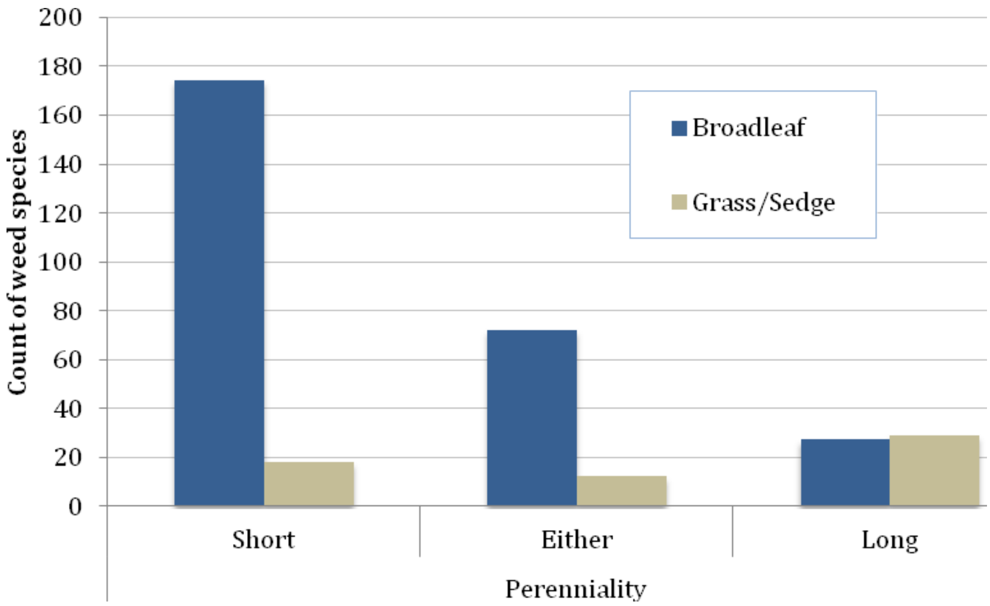

Figure 3.1 Count of distinct weed species identified during industry consultation, classified by perenniality: short (annual and/or biennial), either (variable or uncertain perenniality), or long (perennial); and weed type: broadleaf or grass/sedge (n = 83).

3.2. Most common weeds and their impact

While identifying the most important weeds of Australian vegetable production, we asked industry stakeholders to summarise the key impacts of each weed, in the areas of crop yield and quality, farm management, and other impacts. Where possible, stakeholders were also asked to rate the importance of each weed species on their farm or in their district. WA focus group participants pointed out that 'most important weed' is a subjective issue and depends on district, crop, soil type and time of season. In NT, weed importance varies from wet to dry season.

Generally, the impact of weeds in vegetable production as revealed through industry consultation confirmed the findings of the literature review. That is, weeds have an economic impact on the farmer, reduce yield, impact on the quality of produce, and can make management of the crop more difficult (Appendix 1, Section 3). Many farmers noted that weeds with functional similarly to their crops had the greatest impact. These were also the most difficult to control, often due to lack of selective herbicide options. In general, broadleaf weeds will be difficult to control in a broadleaf vegetable crop. Reported examples include amaranthus (*Amaranthus* spp.) in pumpkin crops in NSW, capeweed (*Artotheca calendula*, Figure 3.2) in lettuce crops in WA and SA, and wild radish (*Raphanus raphanistrum*) and wild turnip (*Rapistrum rugosum*) in brassica crops in NSW, WA and SA.

*Figure 3.2 Capeweed (*Artotheca calendula*) was found to be a problem in lettuce crops in WA.*

The research suggested that weeds in vegetable crops can generally be grouped on the basis of their ecology and reproductive habit into two functional groups:

- heavy seeding annual or biennial weeds, or
- weeds with persistent underground parts, generally biennial or perennial.

Because many of the weeds in each group behave similarly within vegetable crops, and are controlled using similar methods, we discuss below the two most commonly reported examples from each group: fat hen and nutgrass. Reference is made to other notable weeds within each group to illustrate commonality.

*3.2.1. Fat hen (*Chenopodium album*)*

This heavy seeding annual or biennial broadleaf weed is noted for its impact on the yield and quality of a range of vegetable crops in Australia (Figure 3.3). If allowed to grow large enough, fat hen infestations can compete with crop plants for light, nutrients and moisture, and have the capacity to smother crops. Fat hen was noted by a farmer in Qld for its capacity to grow and seed quickly, while another Qld farmer noted that it interfered with harvest machinery (green bean harvesting). Other functionally similar weeds that interfere with harvesting due to their size or density include amaranthus (a noted problem around Tennant Creek, NT), and caltrop (*Tribulus terrestris*). Interference also includes weeds that have prickles which may sting field staff during manual harvesting or weeding, including stinging nettle (*Urtica urens*), caltrop and common thorn apple (*Datura stramonium*).

*Figure 3.3 Fan hen (*Chenopodium album*) on a farm near Gatton, Qld.*

Fat hen is notable for its ability to host insect pests of vegetable crops such as aphids, an issue that was noted by focus group participants in NSW (as an issue in cucurbit crops), and by focus group participants in Vic (in a range of crops). Other functionally similar weeds that were considered to host pests, diseases and viruses included wild radish, stinging nettle and blackberry nightshade (*Solanum nigrum*) in brassica crops in SA and NSW, milk thistle (*Sonchus oleraceus*) in tomato crops in WA, and pigweed (*Portulaca oleracea*) in a range of vegetable crops in NT.

For others in the industry, crop contamination is a significant issue with fat hen, particularly in leafy vegetable crops. A Tas farmer noted its capacity to contaminate cut leaf harvest, resulting in significant cost in removing the contamination by hand during processing and packaging. Similar reported examples include pigweed (contaminating lettuce and brassica crops in WA), wild radish (seed contamination of brassica crops in Tas), and wild turnip contamination of brassica crops in Tas and NSW.

Fat hen was considered the most important weed by a farmer in Qld in all crops, and equal top rank amongst NSW focus group participants in all crops. In many other cases, fat hen was rated either the second or third most important weed on a farm or in a vegetable growing district. This weed is therefore of considerable importance to vegetable farmers, in addition to being commonly found across the industry.

Many of the other commonly reported short lived broadleaf weeds are likewise of high importance in many vegetable growing districts across Australia. Fat hen is representative of these weeds in its impact within vegetable crops, and in the difficulty in managing such weeds in a broadleaf crop. Other commonly reported short lived, heavy seeding weeds included stinging nettle, mallow (*Malva parviflora*), pigweed, amaranthus, wild radish, blackberry nightshade, and milk thistle. Many grass species are functionally similar to these broadleaf weeds in their short lived heavy seeding behaviour, such as summer grass (*Digitaria sanguinalis*), ryegrass (*Lolium rigidum*), and winter grass (*Poa annua*). However, these are generally less difficult to manage in conventional vegetable production due to a greater variety of selective herbicide options. Grass weeds are more noted for their impact in organic production, or where herbicide resistance occurs (Section 5.1.5).

*3.2.2. Nutgrass (*Cyperus rotundus*)*

Nutgrass was the fourth most commonly identified weed during this project, but is functionally different to the short lived, heavily seeding broadleaf weeds that are most common in vegetable crops (Figure 3.4).

In addition to being a perennial species, nutgrass persists underground through small tubers or 'nuts' which are formed on rhizomes, and give rise to new shoots and rhizomes. Nutgrass is reported as one of the world's worst weeds, and occurs across Australia (Auld and Medd 1992). Similarly behaving weeds with persistent underground parts that were reported during this project include *Oxalis latifolia* in Tas, oxalis or soursob (*Oxalis pes-caprae*) in NSW, Vic and SA, couch (*Cynodon dactylon*) in NSW, SA, NT and WA, and kikuyu (*Pennisetum clandestinum*) in SA. Oxalis species survive for long periods under the surface via bulbs or deep roots, that can stay dormant for long periods.

If dense nutgrass infestations establish, they are capable of choking out or suffocating vegetable crops, reducing yield, and possibly causing a complete crop loss – an issue highlighted by farmers in Qld and WA. Similarly, kikuyu was noted for its capacity to cause total crop loss on an organic farm in SA. In conventional farms, though, kikuyu and couch grasses appear to be a less significant problem, due to the availability of non-selective fallow, pre-emergent and in-crop selective herbicides to manage most grasses.

*Figure 3.4 Nutgrass (*Cyperus rotundus*) plant parts, plant removed from a lettuce crop near Gingin, WA.*

Nutgrass is a significant problem in crops where plastic mulch is used. It is capable of piercing the plastic film (Figure 3.5) and attaching clods of soil to the underside, making it more difficult and expensive to dispose of plastic after harvest, as it is heavier to remove from the field, and disposal charges are sometimes by weight (such as in the Richmond district in NSW). Piercing of the plastic was noted in NSW and NT, while NSW farmers also noted that nutgrass has been seen to pierce plastic drip irrigation tape. Nutgrass can also reduce the quality of root vegetables by piercing the crop – a phenomenon noted by project participants in Qld (in carrots), in NSW and NT (in potatoes), and in WA (in onions).

Figure 3.5 Nutgrass piercing plastic mulch in a cucurbit crop near Bundaberg, Qld (Source: Sindel et al. *2011).*

Some success controlling nutgrass with the non-selective herbicide glyphosate, or with the pre-plant herbicide oxyfluorfen, was reported by farmers in NSW. However, reports from SA and WA suggested that non-selective options such as glyphosate and paraquat/diquat did not work effectively. Likewise, farmers in Tas and SA reported difficulties in controlling oxalis and soursob with non-selective herbicides, or pre-plant/pre-emergent options such as oxyfluorfen. A farmer in Qld also noted that using non-selective herbicides to manage nutgrass required that a fallow period be maintained, and our observation is that fallow periods are rarely practical in busy, year-round vegetable producing regions such as Werribee South in Vic and Richmond in NSW.

Farmers and agronomists in NSW considered that ongoing cultivation was important in *eventually* controlling nutgrass successfully, though agronomists in SA suggested that cultivation was a major cause of nutgrass spread. A farmer in WA had been able to keep his farm clean of nutgrass through diligent farm hygiene practices (see also Sindel *et al.* 2011 for an example of a farmer near Bundaberg, Qld, keeping his farm largely clean of nutgrass through effective hygiene). A farmer in NT had recent success with nutgrass control in his vegetable crops, but was unwilling to share confidential information on his approach.

Nutgrass was often considered the worst or one of the worst weeds on farms or in districts, including the Katherine district in NT, Richmond in NSW, northern Qld, around Mildura in Vic, south-western WA, and on various farms in Vic, WA, Qld, and NT. No instances of nutgrass infestation were reported by Tas project participants, suggesting that this weed may be less of an issue in that state.

3.3. Other notable weeds and their impact

Many weeds were only reported on a limited number of occasions during this research, but are significant in particular districts or on particular farms for a variety of reasons. Some examples include:

- London rocket (*Sisymbrium irio*, Figure 3.6), only found on a farm near Gatton, Qld, after the 2011 floods in that district. On this farm, the herbicides pendimethalin and bromoxynil had been tried without success to manage London rocket, while chipping was ineffective as the weed has thick roots and resprouted readily. London rocket seed contaminated and rotted broccoli heads, and was the main problem weed in this crop.
- Johnson grass (*Sorghum halapense*) was the major problem weed for a sweet corn farmer near Richmond, NSW. It overwhelmed the crop for all resources, and because it is functionally similar to sweet corn plants, no selective herbicide options were available. Cultivation spreads the weed's reproductive parts easily, and thick infestations are a crop management issue. Crop rotation was considered useful in managing the weed, allowing the selective herbicide fluazifop-p-butyl to be used in broadleaf vegetable crops.
- Instances of glyphosate resistant ryegrass (*Lolium rigidum*) were reported in Tas and WA, to the extent that this weed was considered one of the most important in Tas by focus group participants. Resistance means that ryegrass can compete heavily with crop plants, grow in clumps, interfere with harvest, and seed prolifically. In WA, resistant ryegrass competes heavily with carrot crops on infested farms, and interferes with the harvest of carrots and cut leaf crops.
- Chickweed (*Stellaria media*) was relatively widely reported, but was noted as the most important weed in the district by focus group participants in Werribee South, Vic. This weed is mainly a problem in the district in autumn and winter, and smothers crops such as cauliflower and other brassicas. Some farmers were reluctant to use herbicide options available to manage this weed in some crops, due to cost, concerns over residue, or experiences with herbicide ineffectiveness.
- Cleavers (*Galium aparine*) was considered a most important 'sleeper' weed in the Devonport/La Trobe district by focus group participants in Tas. Participants believed this weed had only been present in Tas for around a decade, and saw it as a future weed of considerable importance for the state. Cleavers makes harvesting difficult, reducing the yield of carrot crops by tangling with the harvest equipment. It spreads rapidly, and no effective herbicides were believed to be registered in Australia for its management. Participants mentioned two herbicide options from the UK – metoxuron (now discontinued), and prosulfocarb (available in the UK and registered for control of cleavers, but not available in Australia currently – see Section 5.1.1).

*Figure 3.6 London rocket (*Sisymbrium irio*) on a farm near Gatton, Qld – an example of a weed with a significant local impact.*

4. Current weed control methods

Various weed control options are currently available to Australian vegetable farmers. Most are suitable at certain times of the season, or for particular management circumstances. These options may be categorised as 'preventive methods' (reducing weed emergence in crop beds before crop establishment), 'direct physical methods' (used directly in the crop after sowing or transplanting), and 'cultural methods' (enhancing crop competitive ability). Techniques from each of these categories should be implemented to achieve sufficient control of weeds (Melander *et al.* 2005).

It is rare for the weed control methods described in this chapter to be used in a vegetable crop in isolation. Nearly all Australian farmers integrate a number of these techniques into a weed management strategy, because no single technique alone will effectively manage weeds in the crop during the entire growing season. 'Integrated Weed Management' (IWM) is discussed in more detail in Section 4.6.5.

Tables 4.1 and 4.2 show the mean effectiveness and affordability of the various weed control methods currently available, according to respondents to the national survey. These data are not statistically significant, given the low survey response and the fact that each respondent only rated those methods they had experience with. Nonetheless, the results display trends that reinforce the discussion of individual methods in the following sub-sections and are consistent with results reported for herb and vegetable farmers in Australia (Kristiansen *et al*. 2007).

*Table 4.1 Mean **effectiveness** of weed control methods (national survey respondents, where 1 = 'Not Effective' and 5 = 'Highly Effective')*

Method	Effectiveness
Chipping and hand weeding	3.6
Precision agriculture	3.5
Fallow herbicide application	3.3
Plastic mulch	3.3
Tillage during fallow and before sowing or planting	3.3
Stale and false seedbeds	3.2
Pre-emergent herbicide application	3.1
Biodegradable mulch	3.0
Weed sensor technology	3.0
Post-emergent herbicide application	2.9
Crop rotation	2.9
Shielded inter-row herbicide application	2.7
Farm hygiene	2.6
Inter-row tillage	2.5
Permanent beds and controlled traffic farming	2.3
Increased plant density	1.4
Organic mulch	1.0

*Table 4.2 Mean **affordability** of weed control methods (national survey respondents, where 1 = 'Not Affordable' and 5 = 'Highly Affordable)*

Method	Affordability
Fallow herbicide application	4.4
Stale and false seedbeds	3.9
Crop rotation	3.8
Inter-row tillage	3.7
Pre-emergent herbicide application	3.6
Tillage during fallow and before sowing or planting	3.5
Farm hygiene	3.4
Permanent beds and controlled traffic farming	3.3
Precision agriculture	3.3
Post-emergent herbicide application	3.1
Shielded inter-row herbicide application	3.0
Increased plant density	3.0
Plastic mulch	1.7
Chipping and hand weeding	1.6
Biodegradable mulch	1.4
Weed sensor technology	1.2
Organic mulch	1.0

4.1. Chemical controls

4.1.1. Current registered herbicides in Australia

At the time of writing (July 2014), we identified 37 herbicides registered for management of weeds in vegetable crops in Australia (see Attachment 1, Table A1 at the end of this report). Many of these are available under multiple trade names. Some are registered for use within a single vegetable crop variety, though most are registered for use within several vegetable crop varieties.

Application timing for the majority of options is before crop emergence or planting (Section 4.1.3). There are a number of post-emergence options for selective control of weeds within a growing vegetable crop. However, these are often limited to management of grass weeds in a broadleaf vegetable crop, or management of a limited range of broadleaf weeds (Section 4.1.4). Some non-selective herbicides are also registered. Common uses for non-selective herbicides in vegetable production includes post-harvest paddock clean-up or fallow management (Section 4.1.5), or shielded application to inter-row spaces, wheel tracks, irrigation channels and lines, or headlands (Section 4.1.6).

4.1.2. Minor use permits

In addition to the herbicide registration system, the Australian Pesticides and Veterinary Medicines Authority (APVMA) maintains a minor use permit system, which allows for legal use of chemicals where the herbicide is not currently registered for that use. Vegetable farmers or their agronomist are able to request a minor use permit through HAL, who then work with the registrants to obtain a minor use permit from the APVMA (Woods 2014).

In late June 2014, there were 60 minor use permits in force in Australia, covering 22 distinct herbicides. Many of permits allow use in several or all Australian states. The minor use permits are listed in Attachment 1, Table A2, at the end of this report.

Minor use permits allow vegetable farmers access to different herbicides in their crops, where these herbicides have been shown to have some efficacy. Most of the herbicides listed in Table A2 are already registered for other vegetable crops. Many of the minor use permits cover all states except Vic, limiting the minor use options available to Victorian farmers.

Several project participants expressed an opinion that HAL and AUSVEG need to do more to support farmers and agronomists to facilitate off-label use of herbicides through minor use permits. Services currently available are discussed further in Section 6.2.3.

4.1.3. Pre-emergent herbicide application

Pre-emergent herbicides generally control a wide range of weed species, and are used before crop planting or crop emergence. Choice of pre-emergent or pre-plant herbicide depends on the weed species causing difficulty, the following crops and relevance of plant-back periods for the herbicide, and the types of herbicides used previously. Herbicide rotation is recommended where possible to avoid weed resistance to commonly used herbicides (Qld DAFF 2012; 2013). Some crop damage is possible with pre-emergent herbicides under certain circumstances (Appendix 1, Section 5.1.1). Success with pre-emergent herbicides may depend on minimising the time between final bed preparation cultivation and pre-emergent herbicide application, and minimal soil disturbance to maintain the 'herbicide blanket' (Appendix 1, Section 5.1.2).

A range of pre-emergent herbicides were used by vegetable farmers consulted for this project, including pendimethalin, propyzamide, s-metolachlor, oxyfluorfen, propachlor, and chlorthal-dimethyl (Figure 4.1). Pre-emergent herbicides are incorporated with a light till (used in combination with pre-plant tillage, according to a farmer from Vic); 'rolled' into the crop beds; or applied to beds that have been formed for transplant, or in which seeds are about to germinate. Depending on the crop, some crop tissue damage was noted, although for other farmers the crop was not adversely impacted by pre-emergent application. Residual periods make it difficult for farmers to use some herbicide options. For example, a farmer in WA had used s-metolachlor in their spinach crop, but found the long residual period made it difficult to manage their following lettuce crop.

Figure 4.1 Applying pendimethalin (Stomp) pre-plant to lettuce beds near Gatton, Qld. Pendimethalin is an effective and commonly used pre-emergent herbicide, but can stunt lettuce crop growth under certain conditions (Qld DAFF 2010).

Effectiveness and affordability

The survey of vegetable farmers conducted for this project found that pre-emergent herbicides appear to be both relatively effective and affordable for weed control in vegetable production (Tables 4.1 and 4.2).

Overall, farmers, agronomists and researchers considered that pre-emergent herbicides were an effective option, depending on crop and weed species. That is, pre-emergent options may not be available in some crops, or suitable to management of some weed species. Factors behind the *effectiveness* of pre-emergent herbicides include:

- *Soil moisture*: farmers from Vic stated that the soil must be damp for pre-emergent herbicides to be effective. Similarly, a farmer from NSW felt that pre-emergent herbicides had been less effective in the past couple of seasons, and that this was probably due to the dry weather.
- *Usage rate*: farmers from Vic emphasised that correct recommended rates should be used for pre-emergent herbicides, and not 'half rates', as they had observed on some other farms. They considered that applying herbicides at lower than recommended rates would always be ineffective. Several farmers stated that they applied pre-emergent herbicides at lower rates, often because of concern that the herbicide will stunt crop growth. Some of these found that the herbicides were less effective than expected, or that their effectiveness appeared to be declining. However, one such farmer suggested that pre-emergent herbicides were 'not really effective, but were better than using no herbicides at all'. In contrast, a farmer in Tas applying pre-emergent herbicides at recommended rates found this method to work effectively.
- *Maintaining the 'herbicide blanket'*: as the literature suggests, minimal soil disturbance is required to maintain an effective pre-emergent herbicide blanket after application. Participants in the NT focus group noted that the herbicide pendimethalin required minimal traffic in the beds after application to be effective in stopping weed germination.
- *Timing*: application timing depends on herbicide and crop, but may be before transplant or crop emergence, or within a day of crop transplant into the crop beds. A farmer in NSW stated that timing was critical for effective control of weeds with pre-emergent herbicide, allowing the crop plants to effectively out-compete later germinating weeds.

There was a consensus amongst farmers and others consulted that pre-emergent herbicides were a significant expense for the farmers, but that they represented good value for money, building an effective foundation for weed management throughout the life of a crop. Two farmers from Vic stated that while expensive, pre-emergent herbicides were a more cost-effective option than employing staff to hand weed later in the life of a crop. Likewise, participants in the Vic focus group considered them to be less expensive than post-emergent herbicides. A farmer from Qld stated that 'pre-emergent herbicides are only expensive when they don't work!'.

Focus group participants in Tas, Vic and WA considered pre-emergent herbicides to be a very important weed control method, with those from Vic considering it the most important.

4.1.4. Post-emergent herbicide application

Post-emergent herbicides are most often registered for control of grass weed species in broadleaf vegetable crops. Grass weeds are rarely a problem in conventional vegetable production, as several post-emergence herbicide options are available to manage grass weeds. However, not all grass weeds may be managed this way, and farmers need to be aware of the potential for herbicide resistance. In organic vegetable production, grass weeds appear to be as significant a problem as broadleaf weeds, because selective post-emergent herbicide use is not an option. For example, an organic farmer in SA had significant problems with kikuyu, and spent considerable time managing this weed through hand weeding, slashing and attempting to ensure effective crop plant competition.

Tables A1 and A2 in Attachment 1 confirm that there are relatively few selective post-emergent herbicides available for controlling *broadleaf* weeds in vegetable crops. Post-emergent broadleaf control herbicides currently registered in Australia include:

- Bentazone (in beans);
- Bromacil (in asparagus);
- Cyanazine (in onions, peas and sweet corn);
- Fluazifop-P-Butyl (in brassicas);
- Ioxynil and methabenzthiazuron (in onions);
- Linuron (in carrots and onions);
- Phenmedipham (in beetroot and silverbeet); and
- Rimsulfuron (in tomatoes).

Products used by farmers consulted during this project included s-metolachlor, linuron, bentazone, fluroxypyr (in sweet corn on a NSW farm), fluazifop-p-butyl, clethodim, sethoxydim (now discontinued), and prometryn. Farmers in Qld, Tas and NSW were using phenmedipham to manage broadleaf weeds in lettuce crops under a minor use permit. Post-emergent broadleaf weed control options for major vegetable crops in Australia such as potatoes, lettuce and cucurbits are restricted to other options within the crop beds, such as plastic or biodegradable mulch film, hand weeding or intra-row tillage (Qld DAFF 2010; Sindel *et al.* 2011).

Effectiveness and affordability

Post-emergent herbicides were considered overall by survey respondents to be somewhat less effective and affordable than pre-emergent options, though still overall are neither ineffective nor prohibitively expensive (Tables 4.1 and 4.2).

Research participants in NSW, Tas and Vic focus group pointed out, the effectiveness of this option is therefore heavily dependent on crop. In many crops, there are no post-emergent herbicide options, particularly for broadleaf weeds. Focus group participants in Tas considered post-emergent herbicides to be crucial to integrated management within vegetable crops where options were available. When used in such a way, these herbicides were effective in managing weed populations.

Where the crop and weed species suits, post-emergent herbicides give farmers some chance of managing weeds within crops that have a longer growing period. A farmer in WA stated that post-emergent herbicides were crucial within their onion crop, with a six month growing period.

Similarly, a farmer in Tas stated that the long winter growing period of their lettuce crop made grass herbicides, as well as the broadleaf herbicide phenmedipham a good option, given their longer withholding period and the capacity to make more herbicide applications. This farmer believed that phenmedipham was effective against all major weeds in their lettuce crops, and that continuation of its minor use permit was vital. However, a researcher in Qld stated that this herbicide may have been classed as high risk and marginal return in lettuce crops. Likewise, WA focus group participants stated that long withholding periods made it difficult to consider post-emergent herbicide use in lettuce, given its short growing period in this state compared to winter lettuce production in Tas.

Participants in the Vic focus group considered post-emergent herbicides costly, but worthwhile, and the second most important weed control method available. However, a Vic farmer interviewed separately considered post-emergent options too expensive to consider using.

4.1.5. Fallow herbicide application

Non-selective options for managing weeds during crop fallow periods may include carfentrazone, glyphosate, diquat, paraquat, paraquat/diquat, and shirquat (see Attachment 1, Table A1). Products used to manage weeds during the fallow period by farmers interviewed for this project included pendimethalin, glyphosate, paraquat/diquat, and glufosinate-ammonium.

Fallow periods vary depending on region, When used, fallow periods generally occur in summer (noted by farmers in WA and Tas), although fallow herbicide application may occur in the spring (occasional use by a farmer in Vic), during the wet season in the NT (where aerial application is often needed on wet fields), or on an ad hoc basis as the crop rotation permits (as noted by another farmer in NT) (Figure 4.2).

Figure 4.2 Fallow paddocks such as this one near Darwin, NT, can be an important weed refuges if careful fallow management (such as herbicide application) is not undertaken.

Effectiveness and affordability

Amongst survey respondents, using herbicide to control weeds in vegetable fields during crop fallow periods was considered one of the most effective weed management strategies, as well as being the most affordable (Tables 4.1 and 4.2).

Farmers consulted during the focus group meetings and farm visits confirmed the affordability of fallow herbicide application, and suggested it was also an effective way to manage weeds where fallow periods were possible. A farmer in Tas applies glyphosate to the fields post-harvest to clean up both weeds and crop plants, and incorporates the residues into the soil as they can harbour diseases and pests. In WA, a farmer uses paraquat/diquat as part of a fallow management strategy over five months which also includes cultivation and grazing with cattle. An NT farmer uses a helicopter to apply glyphosate during the wet season fallow, while another has successfully used fallow periods to manage nutgrass in his paddocks.

In some regions, year-round production precludes fallow periods or makes them rarely used, so that fallow herbicide application is not particularly relevant. A farmer in Vic noted that they will use fallow herbicide application, but that fallow periods are rare, while another in NSW stated they would only do it if they had time. This farmer also noted that the fallow application needs to be irrigated in, and the risk of spray drift using non-selective herbicides makes this approach potentially very costly.

4.1.6. Shielded inter-row herbicide application

Shielded application of herbicides normally involves using a non-selective herbicide (see Table A1) to manage weeds in non-crop spaces such as headlands, irrigation lines and channels, and around other infrastructure (Figure 4.3 and Figure 4.4). Shielded spraying may also be used between the crop beds or rows (*inter-row spraying*), to manage weeds that may either impact on the crop directly, or host pests and disease. This form of herbicide application carries some risk of crop damage due to drift even when using a shielded spray unit. This risk can be minimised by using wider crop row spacing and larger droplet sizes, however some farmers may choose other weed management options if they feel the risk is too great (Sindel *et al.* 2011). Farmers applying this method generally use non-selective herbicides for shielded inter-row spraying such as glyphosate or paraquat/diquat, or glufosinate-ammonium. Shielded inter-row herbicide application is an alternative to inter-row tillage (discussed further in Section 4.2.3).

Figure 4.3 Shielded inter-row herbicide unit, Bundaberg Qld (source: Sindel et al. 2011)

Figure 4.4 Irrigation lines controlled for weeds with shielded non-selective herbicide application, near Adelaide, SA.

Effectiveness and affordability

Farmers who completed the online survey for this project considered shielded inter-row herbicide application to be only a moderately effective weed control method, as well as being somewhat effective (Tables 4.1 and 4.2).

Several farmers consulted for this project confirmed that the potential for crop damage means that shielded inter-row spraying was too risky for them to consider. An indeed, a farmer in SA using a shielded unit to control weeds in his irrigation lines felt that the approach did not manage weeds very effectively, and still experienced crop damage as a result due to spray drift. Some farmers used non-herbicide alternatives such as scuffling/tillage to manage weeds in between the crop beds, and farmers in both Tas and Vic felt that this approach was sufficient, without having to resort to herbicides. Other farmers did not consider weeds in these spaces to be an issue for their crops, or felt that the technique was not warranted where the inter-row space comprised of narrow wheel tracks. In NSW, another farmer had tried shielded inter-row herbicides, but was concerned about the risk. This farmer irrigated all crops using drip lines to reduce moisture in the wheel tracks, and limit weed growth. One farmer in NT used shielded herbicides effectively to manage weeds in the wheel tracks, but crucially set the shielded unit right at ground level, so that the wheel tracks were covered without any chance of drift onto the raised crop beds.

4.1.7. Spot-spray herbicide application

Farmers attending the WA focus group meeting suggested that spot-spraying with a non-selective herbicide within the crop was an option, particularly for dense infestations of nutgrass which could not be controlled effectively with other methods. One farmer at the meeting suggested they would be prepared to sacrifice a portion of their crop to control severe nutgrass outbreaks. Another farmer in WA used a hand-held shielded spray unit rather than a tractor-mounted implement to carry out inter-row herbicide application, due to concern over possible crop damage.

4.1.8. Fumigation

Fumigating the soil in the formed crop beds using broad spectrum chemicals such as methyl bromide and metham-sodium has been a common practice amongst Australian vegetable producers, largely for its benefits for managing nematodes, diseases, and insect pests. However, fumigation may have secondary weed control benefits, and render herbicide use unnecessary in some circumstances (Dimsey 1995; Henderson and Bishop 2000; Ullio 2004; Qld DAFF 2010).

Chemical fumigation faces an uncertain future due to environmental and social concerns (see Appendix 1, Section 6.1.5).

Effectiveness and concerns

The fumigant metham is listed in Attachment 1, Table A1 as a registered fumigant for vegetable crops in Australia.

Fumigation is not widely used by farmers consulted for this project, though it does appear to be a relatively common practice in WA. Farmers in this region noted that fumigating the soil gave them an opportunity to plant a four week crop without any weed issues. As such, it has largely replaced hand weeding for some farmers in south-west WA for short-term crops, and is an effective weed control method. One WA farmer did believe that fumigation was less effective in sterilising weed seeds than it had been in the past, but was considering trials of fumigation for summer weed control.

Despite using fumigation because of the benefits it delivers them, WA farmers were nonetheless concerned about several negative issues associated with its use, such as drift, impact on soil health, smell and the negative perception of neighbours in urbanising areas, and the human health side effects of its use. Elsewhere, farmers using fumigation noted the cost of fumigants, and the danger it posed for machinery operators. A farmer in Vic said that fumigation was ‘a last resort’.

Biofumigation may also be a viable alternative to fumigation, and is discussed further in Section 4.4.4.

4.1.9. Bioherbicides

Sindel *et al.* (2011) found that there were a number of bioherbicide options available to vegetable farmers outside Australia, and these are largely used by organic farmers. An organic farmer in NT used some sprays such as eucalyptus oil for weed management, but was aware of the potential impact on soil pH. Another organic farmer in Qld used pine oil in his organic crops, but only as an occasional (and less effective) backup to thermal weed control. This farmer also made us aware of the bioherbicide 'Degerminator', listed in Attachment 1, Table A1. This product is designed to degrade weed seed protective coating, and render seed unviable for germination. However, we did not speak to any farmers using this product to evaluate its effectiveness.

Two project participants noted that humic acids can be applied to crop beds through drip irrigation, and have some impact on the capacity of weed seeds to germinate. Humic acids were used by a farmer, in conjunction with a sorghum green manure crop, to improve soil health.

4.2. Mechanical weed control

4.2.1. Chipping and hand weeding

In many vegetable crops, chipping and/or hand weeding is the only feasible way to manage weeds within the crop rows at later stages of the crop given the lack of selective herbicide options, particularly for broadleaf weeds (Figure 4.5). Timing is critical for cost-effective hand weeding. For example, in a vegetable crop where the canopy shades the crop rows completely, the best results are achieved around 7-10 days before canopy closure (Henderson and Bishop 2000; Qld DAFF 2012). Selective hand weeding may be carried out to manage weeds that may interfere with harvesting operations, or to avoid seed set and problems in future crops (Qld DAFF 2010; 2013). A farmer in Vic carried out hand weeding to control heavy patches of mallow in their lettuce crops. In NT, farmers will generally only employ staff to hand weed in crops such as cucurbits where plastic mulch is used. In non-plastic mulch crops, lack of staff and time means that hand weeding generally is not feasible, except perhaps on a small acreage.

Figure 4.5 Chipping in an organic cucurbit crop in NT.

Effectiveness and affordability

Our survey of farmers suggests that hand weeding is the most effective weed control method, but that it is also amongst the most expensive (Tables 4.1 and 4.2).

This finding was supported by our discussion with farmers and other stakeholders during the field trips and telephone interviews. Several farmers and focus group participants commented that hand weeding works very well. Often, it is used to follow up other forms of weed management to tidy up the remaining major weeds in the crop. For example, a farmer in Qld carries out hand weeding as a follow up to scuffling, while another follows up pre-emergent herbicide use with hand weeding, used within the crop once weeds have germinated.

However, farmers also noted that the effectiveness of hand weeding very much depends on the skill of staff employed to do the work. A farmer in WA suggested that hand weeding effectiveness varies from one season to the next, depending on the dedication and skill of casual staff employed to do the work.

All farmers agreed that hand weeding is a very expensive approach, compared to other options available. A farmer in Qld was paying casual staff $25 per hour to hand weed. Because of the high cost, in many cases it is carried out only as a last resort, for example where herbicide or scuffling has failed to manage weeds sufficiently. Its use may also be restricted to high value crops such as lettuce, cabbage or cucurbits where the cost is warranted. Timing is also critical in restricting the cost of hand weeding, as a farmer in NSW pointed out when stating that they only hand weed when weeds are small and easy to remove by pulling out or hoeing. A researcher in WA stated that farmers may let heavily infested crops go rather than go to the expense of hand weeding, instead cultivating the crop back into the soil as a green manure.

Because of the high cost, some farmers agreed that they would never consider hand weeding in their vegetable crops. In other cases, farmers saw hand weeding as being vitally important, such as on a family farm in NSW where no staff were employed, but family members kept up with hand weeding despite the time required.

4.2.2. Tillage during fallow and before sowing or planting

Tillage or cultivation is often used not only to kill existing weeds, but to break seed dormancy and encourage germination of new weed cohorts which are then controlled with a knock-down herbicide or another cultivation before the crop is planted (Stall 2009; Qld DAFF 2010). Most farmers use tillage extensively in their vegetable production system, although excessive tillage can lead to a reduction in soil quality. Pre-sow or pre-plant tillage may be carried out before and during formation of the crop beds, as well as light tillage of formed beds to control flushes of germinated weeds. Tillage appears to be a relatively cheap and easy option for farmers, leaving no herbicide residues and incorporating organic matter into the soil (Figure 4.6).

Tillage during fallow periods is common in districts where a fallow is used, though on farms where year-round production is commonly carried out (such as in Werribee South, Vic and Richmond, NSW), a fallow period is not feasible. However, tillage before sowing or planting was universally used by farmers consulted, often immediately after harvest to incorporate the crop back into the soil. Tillage was always used to form crop beds and prepare the soil for planting. In the NT, farmers may carry out a deep rip cultivation to avoid soil compaction within the crop, but being beneficial for weed management as well. In some cases, light tillage, rotary hoeing or scuffling was carried out on the formed crop beds immediately before planting, though as one farmer in Qld pointed out, the feasibility of doing this depended on soil moisture.

Figure 4.6 An illustration of the stages of crop bed forming near Werribee South, Vic.

Effectiveness and affordability

Confirming previous research and industry extension as summarised in the literature review (Appendix 1, Section 5.2), the national survey suggested that tillage during fallow or before sowing or planting was both a relatively effective and affordable weed management method (Tables 4.1 and 4.2).

A farmer in Qld commented that tillage immediately before sowing or planting was '99% effective', and may allow him to move away from pre-emergent herbicide use in the future. Similarly, a farmer in Tas considered rotary hoeing of the crop beds before planting to be 'a must' for weed management, and that the approach worked very well. A farmer in NSW and another in Vic used tillage in preference to glyphosate application to manage weeds, as they were concerned about herbicide residue in the crop, and the effect of glyphosate on the soil. However, another farmer in Vic combined pre-sow tillage with pre-emergent use. Both farmers believed that their approach worked well in managing weeds. The effectiveness of tillage depends on knowledge of tilling equipment, with a farmer in SA commenting that tillage using his multi-tine agro-plough only worked well if the plough had been set up correctly.

Tillage before sowing or planting is a primary activity of organic farmers, and was considered vital by an organic farmer in Qld, and another in SA. The organic farmer in Qld had considerable success with 'blading', to cut weed roots under the ground with minimal soil disturbance. An organic farmer in NT similarly considered soil disturbance to be a problem, for soil health and weed seed bank stimulation.

For all farmers, tillage during fallow and/or before the crop is sown or planted was considered a cost-effective weed control method.

4.2.3. Inter-row tillage

Inter-row tillage involves tilling or cultivation *between* the crop rows or beds (Figure 4.7), and is carried out at various stages of the crop life, depending on crop being grown (Melander *et al.* 2005; Qld DAFF 2010; Sindel *et al.* 2011). Care must be taken, as late attempts at inter-row weed control using tillage may also damage crop roots that have established in the inter-row space (Henderson and Bishop 2000). Nonetheless, inter-row tillage is a successful weed control strategy in most cases, and generally has no negative impact on the crop (Melander *et al.* 2005). It offers an alternative to inter-row shielded spraying for weed control (Sindel *et al.* 2011; see also Section 4.1.6).

Figure 4.7 Scuffler used for inter-row tillage in Gatton, Qld.

Effectiveness and affordability

Farmers who completed our national survey only rated inter-row tillage as being of moderate effectiveness overall, though considered it one of the more affordable weed control methods available (Tables 4.1 and 4.2).

Though the survey suggested that this method was only somewhat effective for weed control, several farmers we consulted with considered inter-row tillage to be very effective, even though it may be a 'primitive' method according one NT farmer. Nonetheless, *timing* appears to be critical for the effectiveness of this approach, from the perspective of both weed and crop management. A NSW focus group meeting participant summarised this point, commenting that 'too early and weeds recover, too late and the crop can be damaged by cultivation'. A farmer in Qld had success scuffling between the crop rows early in the crop life to avoid crop root damage, while a farmer in Vic noted that late inter-row tillage had damaged crop roots in his crops in the past, reducing final yield.

Potential drawbacks of inter-row tillage noted by farmers included that it only keeps weeds under control for a relatively short period within the life of the crop, and that it can contribute to soil compaction and reduced soil quality. Some farmers do not carry out inter-row tillage, either because they do not consider weeds in the inter-row space to be a problem for their crop yield and quality, or because they are successfully managing weeds in the inter-row space using appropriately timed herbicide application.

Farmers at the NSW focus group meeting considered inter-row tillage a 'critical' weed control method. Farmers at the meeting in Vic considered it to be the third most important method, and one considered introducing inter-row scuffling.

4.2.4. Intra-row tillage

In the case of many vegetable crops (and many significant weeds), shallow tillage *within* the crop rows (intra-row tillage) may be the only option apart from expensive hand weeding to manage weeds within the crop beds, due to a lack of selective post-emergence herbicides for broadleaf weeds, or in crops where plastic mulch is not used (Figure 4.8). More recently, equipment such as the Weedfix cultivator (Figure 4.9) has been developed to allow farmers to till within the crop rows. These options, as well as their benefits and costs as identified in the literature, are discussed in more detail in Appendix 1, Section 5.2.1.

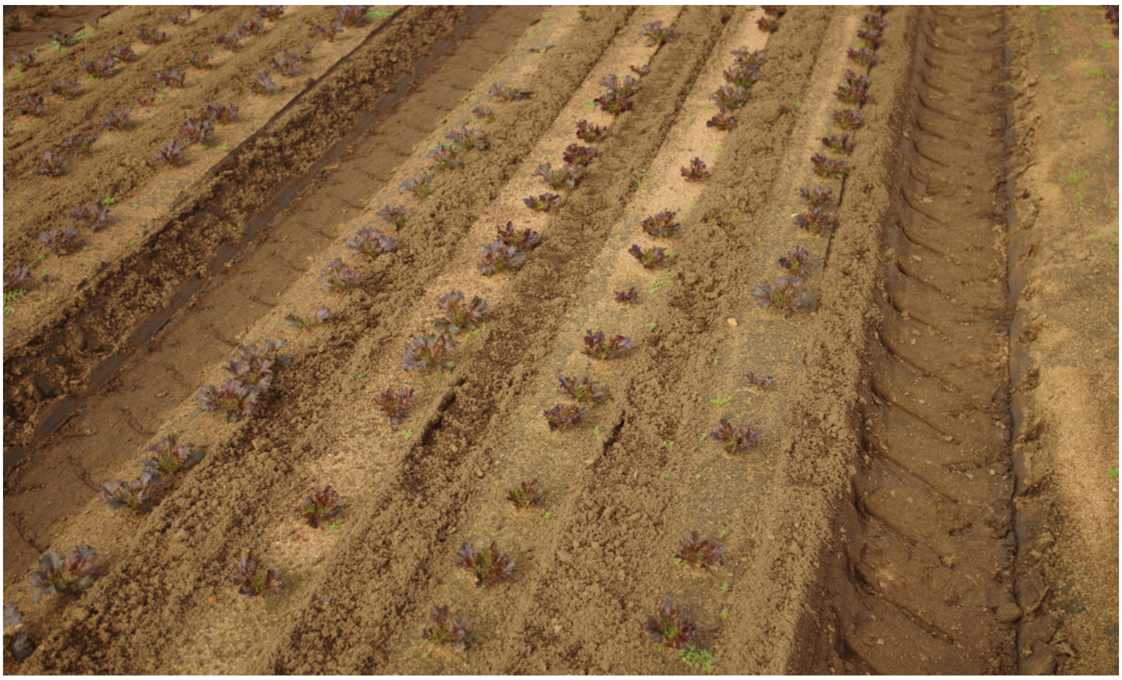

Figure 4.8 Tillage used within a lettuce crop bed near Gingin, WA.

Figure 4.9 Weedfix cultivator used for intra-row tillage near Adelaide, SA.

Effectiveness and affordability

Intra-row tillage was not used by respondents to the national survey (Tables 4.1 and 4.2), however this approach was discussed some farmers and other stakeholders consulted during face to face, focus group and telephone discussion. It appears to be the least likely tillage method to be used for weed control.

A farmer in WA and another in SA carried out intra-row tillage by eye, with neither using GPS to maintain a straight line. The farmer in WA found that the process was time consuming because of the level of accuracy required, but that it works fairly well. He did note, however, the weeds within the crop lines themselves still needed to be managed by hand. The SA farmer uses a Weedfix cultivator, and found the process effective, although he suspected it would be a lot more effective, and faster, if GPS technology was used. An organic farmer in SA used an 'arrowhead' cultivator within the crop rows, but only in their broccoli crop, where the wider plant spacing made this approach feasible. A farmer in Qld using this approach found it to be '100% effective' in broccoli and potato crops, but less so in other crops. Another farmer in Tas used a mechanical weeder within their lettuce crop beds, but noted that exact and consistent distances were required between crop plants for it to be effective. An organic farmer in SA was considering investing in a Weedfix cultivator for her farm. Another organic farmer in SA was considering investing in an S-tyne knife weeder from

Sustainable Agricultural Machinery, but would need to expand their production scale first.

As is the case with inter-row tillage, timing is critical. Too early, and subsequent weed cohorts may have the time and opportunity to establish in the beds, particularly if the intra-row tillage breaks the soil crust or pre-emergent herbicide blanket, or brings fresh weed seeds to the surface to germinate. As a farmer in Vic noted, early intra-row tillage may also result in damage to crop seedlings. Too late, and weeds may be too large to control, or crop plants may have grown too large to make the option feasible.

While some farmers attending the WA focus group meeting found intra-row tillage to be vitally important, others considered that it was far too costly both in terms of time/labour and fuel, and mostly required multiple passes in order to be effective. Nonetheless, farmers at this meeting did agree overall that this is a very important weed control method.

4.3. Mulches

4.3.1. Plastic mulch

Polyethylene plastic mulch is 'the mainstay of weed control in several high value fruiting vegetable industries in Australia' (Henderson and Bishop 2000) (Figure 4.10). Plastic mulch has been available for vegetable production since the 1950s, and revolutionised the production of several vegetable crops (Lament 1993). It is an expensive weed control option, although it is feasible in high value crops such as capsicums, tomatoes, melons and other cucurbits. It delivers a number of other benefits to the crop, including soil moisture retention, water savings, warming the soil, enhance crop yield and quality, delivering earlier-maturing crops, controlling disease, managing aphids (in the case of reflective mulch films), and preventing the crop fruit from resting directly on the soil (Lament 1993; Henderson and Bishop 2000; Heisswolf and Wright 2010; Qld DAFF 2012).

Figure 4.10 Plastic mulch used on a cucurbit crop near Katherine, NT.

Effectiveness and affordability

Overall, farmers who completed our national survey considered plastic mulch to be among the most effective weed control methods, although it is also one of the most expensive (Tables 4.1 and 4.2).

As the literature suggests, the effectiveness of plastic mulch is dependent on crop, with it being feasible only in certain high value crops. Crops where black or white plastic mulch was used amongst farmers consulted for this project included cucurbits, capsicum, eggplant, and peppers. A farmer in Qld had trialled it in their lettuce crop, but found it too costly.

A farmer in Tas suggested that plastic mulch was 'the key' to his weed management strategy in zucchini, capsicum and eggplant, although emphasising that this was in combination with other methods. Farmers generally suggested that plastic mulch was a highly effective weed control method. One farmer in NSW did note that nutgrass can pierce the film layer (see also Sindel *et al.* 2011), though another in Qld was using a pre-emergent herbicide on the crop beds before the plastic mulch was laid, to manage this weed. A researcher in Vic noted that plastic mulch 'was the pre-emergent' for farmers growing relevant crops.

Despite its effectiveness, farmers we consulted in detail confirmed the suggestion in the survey that plastic mulch was a very expensive weed control option. NT focus group participants suggested that plastic mulch purchase, application and retrieval cost approximately $1,200 per hectare. A farmer in Vic confirmed that plastic mulch was too expensive an option for him to consider, particularly given that he was unsure at the time of planting how much his crop would yield, or what price he would receive for its sale.

Nonetheless, in high value crops plastic mulch remains an essential crop management technique, for weed control, soil moisture retention and soil temperature.

4.3.2. Biodegradable mulch

Biodegradable mulch films appear to have been trialled more extensively across Australia since our earlier work on weeds in cucurbit crops (Sindel *et al.* 2011), while awareness of their availability also appears to have grown.

They are designed to last for several months after laying, so that they maintain sufficient weed control and moisture retention during the life of the crop, but degrade to the extent that they may be cultivated into the field post-harvest, leaving no toxic residues in the soil (Heisswolf and Wright 2010; Limpus *et al.* 2012). Research in Italy suggests that annual waste reduction of approximately 400 kg per hectare is possible by using biodegradable mulch films instead of conventional plastic (Razza and Degli Innocenti 2012).

Effectiveness and affordability

Biodegradable mulches have been under evaluation in Australia for more than a decade, and are now being used by some commercial farmers (Limpus *et al.* 2012). The literature suggests that biodegradable mulches have been relatively ineffective and highly cost-prohibitive in the past. However, these issues are becoming less important over time, as producers make improvements and reduce cost, and researchers look further into the best ways to manufacture and apply biodegradable products. The cost of biodegradable mulch film continues to get closer to the combined purchase and disposal costs of conventional polyethylene in some parts of Australia (Appendix 1, Section 6.3).

However, our consultation with farmers and industry experts for this project suggests that biodegradable mulch options still have some way to go to provide a realistic alternative to conventional polyethylene. The farmer survey suggested that biodegradable mulch is considered less effective than plastic mulch, though still may be a relatively effective product in its own right according to respondents. However, it is still viewed as a considerably more expensive option than plastic mulch, and one of the most expensive weed control options available (Tables 4.1 and 4.2).

NSW focus group meeting participants believed that trial work with biodegradable mulch had produced mixed results. However, our consultation with the industry during the course of this project suggested a number of possible shortcomings of biodegradable mulch in its current form:

- *Degradability*: NSW focus group participants suggested that the mulch either degrades too quickly, exposing the crop to weed issues, moisture and heat loss, or that it degrades too late. Trials in NT have similarly shown mixed results, with a successful trial in Darwin matched by an unsuccessful trial in the same district, while further south in the NT it did not break down until too late (Figure 4.11). These trials apparently put farmers off trying biodegradable mulch options in the NT. A farmer in WA would like to try biodegradable mulch, but stated that it would need to last for two years for it to be worthwhile for him.
- *Movement within the crop beds*: NT focus group participants noted that excessive but necessary foot traffic within a crop bed can damage the mulch too early in the crop life cycle.
- *Equipment needs and application difficulties*: NT focus group participants also considered that different mulch laying equipment would be required to apply biodegradable mulch. An NT farmer believed that inability to store the mulch long-term (because it breaks down quickly) made it difficult to consider this option, however he did believe that he would be able to apply it successfully using his existing, adjustable applicator (Figure 4.12).
- *Litter*: farmers in NT and Qld were concerned about the capacity for degrading pieces of mulch film to spread throughout the district and cause a litter problem. This issue was also raised in the Bundaberg district (Sindel *et al.* 2011).
- *Expense*: farmers believe this mulch option is 'still way too expensive'. An NT cucurbit farmer stated that there would be no labour cost in using a biodegradable option in favour of plastic, as he would still need to retrieve the plastic irrigation tape after harvest. However, an extension professional in SA advised that biodegradable t-tape was being developed by 'One World Enviro Solutions', thus reducing the labour time needed in a crop where biodegradable mulch and t-tape are used.

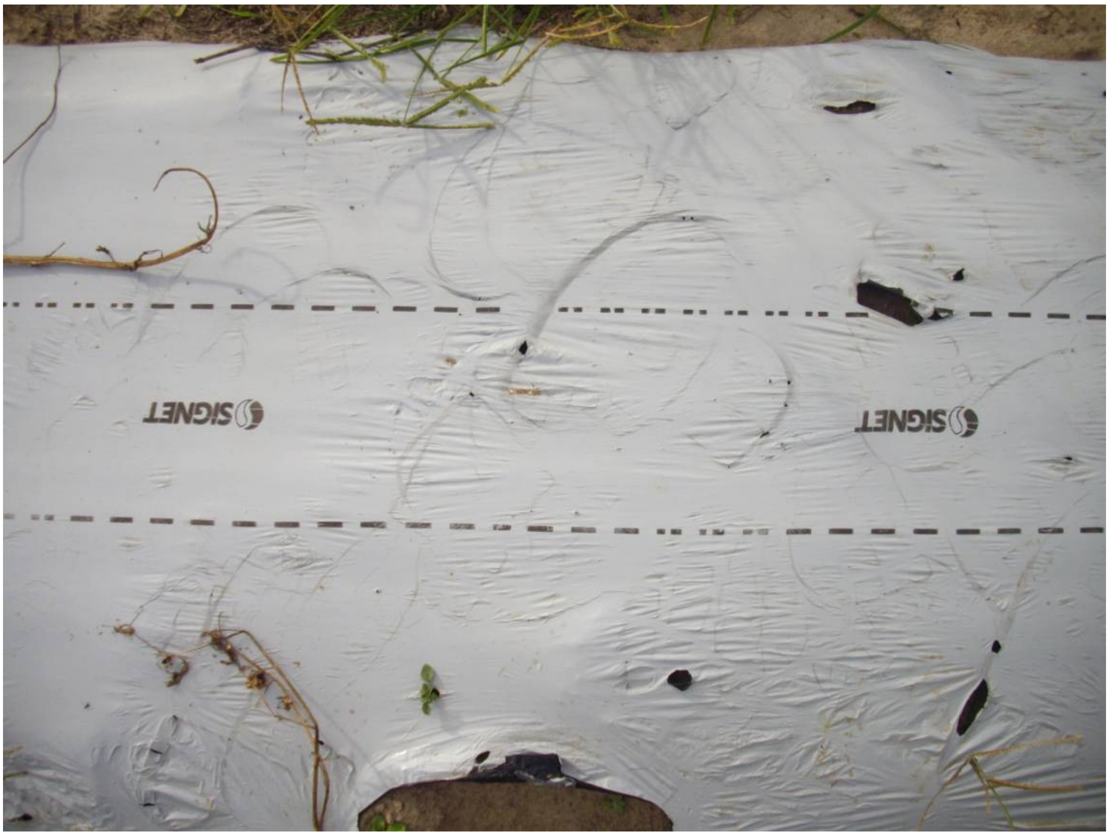

Figure 4.11 Biodegradable mulch film during the breakdown phase near Childers, Qld (Source: M Everett, Research Agronomist, Valencia Ecosystems).

Figure 4.12 Plastic mulch roller for applying mulch film, near Darwin, NT.

Despite these shortcomings, biodegradable mulch appears to have come a long way in the past 10-15 years. It is more commonly used in the Bowen district, where it has been shown to be effective, and where the disposal cost of polyethylene makes this a more attractive alternative (see also Limpus *et al.* 2012). A farmer near Gatton in Qld has trialled biodegradable mulch successfully in a pumpkin crop, while an agronomist in Vic is positive about the future for this product.

4.3.3. Organic mulch

Organic mulch materials are transported to the farm to apply to the crop beds as a mulch, such as sawdust, sugarcane by-products, composted vegetative mulch, forage sorghum hay, recycled newspaper and cardboard cartons, and hessian. They may provide a substitute for plastic mulch, but are most likely to be seen in organic vegetable production. These mulches give farmers the opportunity to improve the health of their soil while suppressing weed growth and retaining soil moisture.

Effectiveness and affordability

Previous research suggests that organic mulches are relatively ineffective in suppressing weeds, to the extent that weeds have an unacceptably high negative impact on crop yield. They can also be expensive and difficult to work with (Appendix 1, Section 5.6). Our national survey of farmers suggested that organic mulches are the least effective weed control option available, as well as being the most expensive (Tables 4.1 and 4.2).

Only a few farmers we consulted during this project used organic mulch, and several of these had only trialled it. In the Richmond district, some farmers have used mushroom compost or composted urban green waste as a mulch in their vegetable crops. The mulch appears to work reasonably well in suppressing weeds for these farmers, though it is mainly used to improve soil health. An organic farmer in SA used straw mulch, either grown on their own farm or purchased from a certified source. However, while the straw is relatively effective on their farm, it has proven to be a vector for ryegrass spread into their vegetable crops.

A farmer in Tas hinted at the impracticality of straw mulch in vegetable crops, stating that they are unable to consider this option because of quality assurance and food safety standards with which they must abide.

4.4. Other weed control methods

4.4.1. Solarization

Solarization involves trapping solar radiation in moist soil for several weeks as an alternative to combined use of black plastic mulch and fumigation. The solar radiation is most often trapped by clear plastic mulch that is laid several weeks before the crop is planted, and as such is most relevant to crops where plastic mulch is used.

While solarization has been found to be effective in research overseas, Australian researchers consider that it is probably economic in Australia (Appendix 1, Section 5.13.3). Focus group participants in SA suggested that solarization was impractical as it took valuable land out of production for too long, and in any event it may not get the soil to a high enough temperature to be effective. Nonetheless, an organic cucurbit farmer in NT considered this an important method in his crops, using black plastic to solarize his soil for six days before the crop is planted.

A common practice in the Gingin district in WA is to leave the paddock fallow, during the hot dry summer months. During this period, weeds germinate but struggle under the conditions, often dying before setting seed. This process is referred to locally as solarization, though is different to the standard form of solarization discussed above. Farmers believed the approach to be effective in managing weeds, but it is only practical where the farmer has enough land to allow a fallow period.

4.4.2. Thermal weed control

Thermal approaches to weed control include flaming and steam weeding. Flaming involves the use of natural gas- or propane-fuelled burners to expose weeds to 'sufficient heat to disrupt cell membranes, destroying leaf and meristematic tissues' (Henderson and Bishop 2000). It is commonly used pre-plant or early post-plant as a replacement for knock-down herbicides. Steam weeding has advantages over flaming, including better heat transfer and reduced fire hazard risk. Furthermore, a comparative trial of steam weeding in Australia found that weed control was equivalent to manual techniques such as tillage and chipping, and to glyphosate (Kristiansen and Smithson 2008). However, these thermal approaches have been found to have significant limitations, including relative ineffectiveness against grass weeds, the need for several treatments, high fossil fuel use, and low work rates (Appendix 1, Sections 5.13.1 and 5.13.2).

Only one farmer consulted during this project was fund to be using thermal weed control. This farmer, an organic farmer from Qld, used flaming as one of his main pre-emergent weed control methods. He considered it affordable and '100% effective' if timed correctly and carried out weekly for three weeks in combination with an irrigated 'stale seedbed' (Section 4.4.11). He is also considering investing in banded steam weeding, combining this with scuffling to manage weeds in the entire crop bed.

However, an agronomist in Tas was concerned about the high environmental impact of thermal approaches because of their demands on fossil fuels, and believed that herbicide use was actually a more environmentally friendly approach for farmers to adopt.

4.4.3. Green manure crops

Green manure crops are sometimes also referred to as 'cover crop mulches' (Figure 4.13). They are commonly used to improve soil quality and structure outside the normal cropping season, and may be used to increase organic matter within a permanent or semi-permanent bed system (Rogers *et al.* 2002; Rogers 2007). Dense green manure crops may also be planted to suppress weeds outside the normal cropping season, including weeds that host pests and diseases. This provides a potentially effective alternative to crop fallow periods which may include non-selective herbicide application to manage weeds. Green manure crop options used by farmers consulted for this project included lablab, cowpeas, blue lupins, oats, fava beans, sorghum, brassicas, barley, and mungbeans. Some farmers in Qld have been noted to grow a green manure crop in their inter-row space for soil health and weed suppression. Similarly, a farmer in SA was considering planting a perennial weed suppressant shrub within his permanent irrigation lines.

'Living and killed mulches' involve using green manure cover crops that have the potential to act as a mulch substitute within a vegetable crop, and may be a substitute to in-crop herbicide application and/or tillage, or plastic mulch film (Rogers 2007). The advantages and disadvantages of green manure crops as a mulch alternative are discussed in detail in Appendix 1, Section 5.7.1. As with organic mulches, green manure crops used as a living or killed mulch may be useful in improving soil health, however their weed management effectiveness appears to be poorer than alternatives such as plastic mulch.

Figure 4.13 Barley used as a green manure crop on a vegetable farm near Currency Creek, SA.

Effectiveness and affordability

Most farmers we consulted use green manure crops for their soil health benefits, with weed control a secondary concern. Only one farmer we spoke to, in Qld, was working towards a killed mulch system in semi-permanent beds, trialling different green manure crops with a 'crimping roller' (Figure 4.14). His success varied depending on cover crop used, and he was still in the trial phase. He noted, however, that this approach would not be as successful for a conventional farmer as excellent soil health was required, something that would take several season to establish on a conventional farm.

However, several farmers did note that their green manure crops appeared to be *effective* in reducing the weed burden in their paddocks. A farmer in SA using barley as a winter green manure suggested it smothered many weeds if sown very thickly, while an organic farmer in SA felt that her use of oats, fava beans, sorghum and brassicas as green manure crops probably helped with weed management. A farmer in Tas had success with weed control when sowing a thick blue lupins crop for its green manure benefits. An organic farmer in Qld used lablab to improve soil carbon and condition in his paddocks, and believed this had reduced his weed burden, arguing that weeds may be a sign of poor soil condition. In addition to the direct benefits of green manure crops in smothering weeds, this option may bring other weed management options into play. For example, a farmer in WA said that planting oats as a green manure crop may allow him to try different selective herbicide options to manage problematic broadleaf weeds of his vegetable crops. However, he was concerned about the potential for herbicide residue to carry over into subsequent vegetable crops. A mixed broadacre/vegetable farm manager in Tas was considering canola as a rotation crop, as it would allow him to use the herbicide atrazine to control glyphosate-resistant ryegrass.

Figure 4.14 Green manure crop 'crimping roller', being trialled on an organic vegetable farm near Gatton, Qld, to provide a cover crop 'killed mulch'.

Several farmers felt that green manure crops were an *ineffective* weed control method, and indeed counter-productive in allowing weeds to flourish in their paddocks. WA focus group participants pointed out that it can be more difficult to control weeds in some green manure crops, and that they therefore increase the weed seed bank, adding to the future weed burden. A farmer in Qld felt that weed seeding increased in his green manure crops, particularly pigweed (*Portulaca oleracea*).

Other drawbacks of green manure crops include taking paddocks out of production for a time and the related opportunity cost of missed crop opportunities. In this way, the real affordability of green manure crops may be questioned by some farmers. They are also not practical in districts where year-round vegetable production is commonplace.

4.4.4. Biofumigation

The uncertain future of metham sodium fumigation has led to increased recent interest in biofumigation. Biofumigation involves using killed green manure crops (Section 4.4.3) to deliver soil fumigation. Some Brassicaceae plants such as canola and mustard release fumigant-like compounds into the soil as they decompose. Where brassica plants are used as a killed mulch, this process is thought to have some positive impact on insects and diseases within vegetable crops, and may have some benefits for weed control as well – both by managing weeds in the crop, and by reducing the seed bank (Henderson and Bishop 2000;

Melander *et al.* 2005; Lefebvre *et al.* 2014). A number of brassica varieties have been developed in Australia for biofumigation and suppression of weeds in horticultural crops (Appendix 1, Section 5.9.1).

Biofumigant mulches used by farmers contacted during this project included 'Caliente' mustard, sorghum (including a 'fumigator' variety), mung beans, millet, vetch, lablab, brassicas, and ryecorn.

Effectiveness and affordability

Several farmers and researchers have undertaken recent trials of biofumigant crops, or intended to in the next season or two. These trials are mainly undertaken for the beneficial impacts of biofumigation on soil disease suppression and improvement to soil structure, while other noted benefits include preventing erosion and adding carbon back into the soil.

Some farmers who had undertaken recent biofumigant trials did not notice any significant reduction in weeds in their paddocks as a result. However, others noticed a reduction in weed burden, including farmers in Tas, Vic, and NT. A number of trials by agronomic companies also appeared to have demonstrated the weed management benefits of biofumigation, including trial work in Tas, Vic, and SA. In Tas, trials reportedly showed that biofumigant varieties make it too 'hot' for weed seeds to germinate when the biofumigant crop is incorporated. One farmer reported that weed seeds germinating in a 'Caliente' mustard crop burn off and die within three days of germination, and that this effect can last for up to four weeks. Agronomic research in SA has shown the weed management benefits of mustard and ryecorn varieties, according to agronomists attending the focus group meeting there.

Disadvantages of biofumigation as reported during industry consultation include a long plant back period into the biofumigated field for a follow-up crop. WA focus group participants noted that additional insecticide treatments would need to be undertaken in the biofumigant crop.

As with a green manure crop, the affordability of a biofumigation treatment is impacted by the need to take a paddock out of production for a time, and the opportunity cost of not being able to grow a crop during this period.

4.4.5. Crop rotation

Crop rotation is commonly used in Australia to give farmers the opportunity to control pests and diseases that impact on vegetable crops. The weed control benefits of rotations are often of secondary importance to many farmers (Henderson and Bishop 2000), as it has a number of benefits for management of other crop pests and diseases, and for soil health improvement. Nonetheless, rotation is a useful weed management tool for controlling many broadleaf species on a farm where vegetables are grown. For example, rotating between broadleaf and narrow leaf crops may allow for different selective herbicides to be used, to manage broadleaf weeds causing problems in vegetable crops (Appendix 1, Section 5.5.1). An example of this comes from a farmer in Tas, who was trialling different crop rotations to manage glyphosate resistant ryegrass.

Several farmers we spoke to had a crop rotation strategy in place, but this was for disease management rather than weed management. Focus group participants in Tas believed that their more forgiving climate allowed local farmers to implement a more varied rotation than elsewhere in Australia, opening the farmers up to more weed management opportunities. Agronomists in SA believe that a 'monoculture' non-rotation production system in Virginia was starting to give way once again to a rotation system on many farms, which would benefit farmers in their effort to manage weeds. Rotating to non-vegetable crops was suggested as an alternative for farmers around Virginia, though this may be impractical due to lack of equipment, knowledge, or skills in working with non-vegetable crops. Rotation is also difficult for some farmers in Vic, because of their need to keep producing the highest value crop (such as a brassica 'monoculture').

Effectiveness and affordability

Survey respondents overall considered crop rotation to be a somewhat effective weed management method, but amongst the most affordable (Tables 4.1 and 4.2).

From the weed control perspective, the main benefit of crop rotation is that it allows farmers to implement different management strategies in different rotation crops. In particular, it expands their pre-emergent and in-crop selective herbicide options at different times of the season. In this way, crop rotation appears to be an effective technique. Farmers in SA, Tas, WA, Qld and Vic all noted the herbicide rotation/option benefits possible within a crop rotation. For example, a farmer in Vic was able to use prometryn for management of some broadleaf weeds in a celery rotation – an option not available to them in their main broccoli crop. Another farmer in Vic found that rotating from broccoli and lettuce had allowed them to reduce the impact of chickweed, one of the most important weeds in Werribee South, in their broccoli crop.

The WA focus group participants confirmed that crop rotation 'is not really a cost' to them, providing commercial crops are grown in rotation. However, focus group participants in Tas suggested there was an opportunity cost to rotation in not being able to continually grow the highest value crops. This appears to be the only notable disadvantage of implementing a crop rotation in vegetable production.

4.4.6. Increased plant density

Farmers may experiment with increasing the density of their crop planting to give the crop a competitive advantage over germinating weeds (Figure 4.15). Where a dense canopy forms, it will be difficult for weed seeds to germinate for lack of light. Weeds are not a significant problem once the crop canopy closes fully (Masiunas 2008), however this is only an option for vegetable crops where the plants are capable of forming a closed canopy (Qld DAFF 2012; Appendix 1, Section 5.10). Similarly, trials in grains in Western Australia suggest that crop rows oriented on an east-west axis (at right angles to the sunlight direction) may suppress weed growth in the inter-row space through more effective shading (Borger *et al.* 2010).

Figure 4.15 Lettuce planting near Gatton, Qld. An ideal planting density will provide some competition with weeds in the crop beds, while at the same time not forcing crop plants to compete with each other for resources.

Effectiveness and affordability

Increased plant density was considered by survey respondents to be ineffective as a weed management method, and somewhat affordable (Tables 4.1 and 4.2).

Considerable variation in effectiveness and strategies used was noted amongst farmers who considered the issue of plant density. Some farmers, such as one in Qld, an organic farmer in SA, and a farmer in NSW, found that an increased density was effectively managing weeds by outcompeting the weeds for space and resources (such as light). The NSW farmer had increased density to 1.5 times its former amount.

On the other hand, some farmers had increased plant density but found this to be counter-productive from the point of view of crop management – crop plants were left to compete with each other for resources. As a farmer in Qld commented, 'more plant cost, less yield, more disease, doesn't make sense'. Others noted that they already planted their crop at the maximum density, and that using transplanted seedlings instead of seed gave the crop plants a competitive head start over germinating weeds in an initially bare crop bed.

A contrasting approach taken by some farmers in recent years was to *reduce* their plant density. A farmer in SA recently increased the space between his plants to avoid intra-crop competition, and to facilitate greater airflow around the plants. Another farmer in Vic similarly reduced plant density to avoid competition, and had not noticed any detrimental impacts on their weed burden as a result. This led them to surmise that their other weed control methods made increased plant density unnecessary.

The extra cost of increasing plant density arises from the need to use more seeds or transplants. Some farmers felt this was justified if it reduced their weed burden, while others believed it did not make sense to spend extra on a strategy which they believed actually reduced their final crop yield.

4.4.7. Farm hygiene

Diligent farm hygiene practices can be used to successfully limit the spread of weeds across and between properties, while poor hygiene practices can allow weed infestations to take hold on farms that were previously relatively weed free (Sindel *et al.* 2011). The range of techniques classified as farm hygiene are summarised in Appendix 1, Section 5.11, and generally include equipment cleanliness (Figure 4.16 and Figure 4.17), restriction or limitation of movement on property (Figure 4.18), and careful product selection. SA focus group participants believed that farm hygiene was more likely to be instituted when the farmer actually owned the land they were growing their vegetables on, reflecting a trend in the Virginia district where many vegetable crops are grown on leased property.

Hygiene practices include restricting the spread of weeds *between* farms (*inter-farm*), as well as restricting spread *across* individual farms (*intra-farm*). Hygiene is often undertaken to restrict the spread of disease as well as weed propagules. Intra-farm hygiene appears to be the more common type, with particularly diligent farmers, or ones employing contractors, focusing on both inter- and intra-farm hygiene. At a broader scale, *inter-region* quarantine practices and regional or state policies are designed to restrict weed spread across Australia. A notable example discussed in the Tas focus group was the effective inspection, quarantine and hygiene practices carried out for contractor machinery coming from the Australian mainland. Similarly, Tas focus group participants highlighted the importance of purchasing certified crop seed, as it is much less likely to contain weed seed, while SA focus group participants noted that weed contamination of the vegetable seedling's growing media has been noticed in the Virginia district.

Figure 4.16 Vehicle washdown near Richmond, Tas.

Figure 4.17 Vehicle washdown bay near Gingin WA.

Figure 4.18 Biosecurity sign near Gingin, WA.

Effectiveness and affordability

Overall, respondents to the survey considered farm hygiene to be only of limited effectiveness as a weed management method, although it was considered to be relatively affordable (Tables 4.1 and 4.2).

Despite the low rating amongst survey respondents, most farmers and agronomists consulted during field visits and telephone interviews agreed that farm hygiene was important to carry out, and that it was a 'must' as part of an effective weed control strategy. A farmer in Tas with glyphosate-resistant ryegrass on the farm, believed that diligent farm hygiene had allowed them to restrict this weed to one paddock on the property. An organic farmer in Qld believed farm hygiene was his most important weed control method, and that it worked very effectively. Many vegetable farmers operate at a relatively small scale, and so do not use contractor machinery, so that inter-farm hygiene is not relevant to them. Agronomists in SA commented that because of this, the benefits of hygiene are perhaps better understood in broadacre cropping than in horticulture.

While farm hygiene appears to be somewhat effective and very affordable, farmers did note some difficulties in using this method to control weeds. In NT, the wet season makes hygiene practices such as machinery washdown difficult. Similarly, it can be difficult to thoroughly wash machinery without spending an inordinate amount of time, an issue noted in both Tas and WA. In the Richmond district of NSW, regular flooding and the small district size means that new weeds tend to spread quickly across all farms, an issue that reportedly contributed to the spread of wild radish in the 1970s. In both this district and in

Werribee South in Vic, the intense year-round production cycle means that farmers generally don't have the time to dedicate to vehicle washdown or other hygiene practices, and therefore consider themselves to have a wide spectrum of weeds on their farms.

Where farmers did *not* agree that farm hygiene was important in controlling weeds, it was because they already felt they had the full local spectrum of weeds on each paddock of their farm, and that it was therefore 'too late' to attempt hygiene. A farmer in Vic made this point, but said that they were considering leasing additional land outside the district, and may implement inter-farm hygiene in this case to stop the spread of weeds between the two properties. A farmer in WA similarly believed that hygiene no longer worked for him, although he continued to carry out machinery cleaning between paddocks.

Farmers from WA and Qld, including the WA focus group attendees, commented that farm hygiene practices are inexpensive and do not take much additional time for the farmer to implement. However, Tas focus group participants believed that undertaking a fully fledged hygiene strategy with the maximum chance of success could become an expensive enterprise.

4.4.8. Permanent beds and controlled traffic farming

Permanent or semi-permanent crop beds provide an alternative to heavily cultivated soil to restrict weed growth, and maintain soil moisture under drip irrigation. The concept of low- or no-till permanent beds may be becoming more acceptable to farmers due to the availability of no-till planters, effective techniques for producing and managing cover crop mulches, and improvements in integrated weed management. This concept has also become popular in broadacre cropping in Australia (Appendix 1, Section 8.1). Permanent or semi-permanent beds may combine effectively with controlled traffic farming (CTF), which involves establishing permanent wheel tracks outside of the crop growing area and in between the permanent crop beds. CTF and permanent beds are discussed in more detail in Appendix 1, Section 5.8.

Effectiveness and affordability

Survey respondents rated permanent beds and CTF relatively ineffective for its potential to control weeds, while being reasonably affordable (Tables 4.1 and 4.2).

This approach was not widely used amongst farmers consulted for the project, however a farmer in Tas said that maintaining a minimal till system, where the crop is planted into a killed 'Caliente' mustard mulch cover crop, was very effective for weed control. A researcher in Qld noted that some farmers were using minimal till to avoid bringing weed seeds to the surface, and were aiming for a system where tillage was only used to renovate the crop beds.

Other farmers in the Lockyer Valley were aiming towards a permanent bed system over the next few seasons, however one suspected it would not be practical in this flood prone district due to soil movement during flood events –

an issue that is likely to be relevant in the Richmond district of NSW as well. Permanent beds are in limited use in NT, according to an extension officer.

4.4.9. Precision agriculture

Precision agriculture is a pre-requisite to CTF and permanent bed systems, as GPS mapping and related technology allows permanent traffic lines and beds to be maintained. However, GPS also allows activities such as bed forming to be carried out to a much higher degree of accuracy, and this was the most common use of GPS amongst farmers we spoke to. Another form of precision agriculture used by some farmers is intra-row mechanical weeding technology, such as the Weedfix cultivator and similar implements (see Section 4.2.4).

Effectiveness and affordability

Although permanent beds and CTF rated poorly for its weed control effectiveness, precision agriculture (a prerequisite for permanent beds and CTF) rated very highly for its effectiveness amongst survey respondents. However, they also considered the technology to be very expensive overall, and a farmer in Vic noted that it was currently too expensive for him to consider investing in (Tables 4.1 and 4.2).

While most farmers taking advantage of GPS technology only use it for their bed forming activities, this still appears to deliver ongoing weed management advantages. For example, a farmer in Qld suggested that using the GPS to ensure straight crop beds made more effective inter-row scuffling possible later in the crop life. Nonetheless, some farmers did use GPS for other crop activities, including herbicide spraying. A researcher in Qld suggested that the spray accuracy delivered by GPS guided machinery helped to minimise crop losses arising from spray drift, while a researcher in WA suggested that precision agriculture-savvy farmers were using GPS technology to map weeds on their farm. The farmers in SA who was using a Weedfix cultivator effectively within their crop rows, believed that combining this implement with GPS in the future would make the system even more effective and efficient.

The main barrier to more widespread use of GPS in vegetable production currently appears to be its high cost. However, a farmer in Tas also noted that GPS was currently impractical on sloping and undulating landscapes such as his hillside farm near La Trobe. Because the GPS units assumed that the landscape was flat, he had observed it to be relatively ineffective in trial work in the district. It may therefore be most appropriate in its current form in flat vegetable growing landscapes such as Werribee South, the Lockyer Valley delta, north Qld, or NT.

4.4.10. Weed sensor technology

Precision management of weeds using weed sensor technology involves detecting individual weed plants amongst a crop, and controlling them with targeted doses of herbicides or targeted intra-row tillage. Automated precision herbicide application has the potential to increase production in vegetable and other crops, reducing herbicide use and reliance on in-crop weed control methods such as hand weeding, and at the same time allowing robust herbicide rates to be used that have a much higher chance of controlling weeds (McCarthy *et al.* 2010; Ferrier and Craig 2011). The technology still appears to be in its infancy and more appropriate to broadacre cropping at the time of writing (Appendix 1, Section 8.3), however it does have potential within vegetable production. A web search reveals a range of research projects and trials of plant sensor technology for pruning, weeding and harvesting, including HAL-funded research projects.

Effectiveness and affordability

Survey respondents were ambivalent about weed sensor technology, although the emergent nature of this technology suggests that farmers may be aware of it, but have not yet seen it in action to form an opinion on its current effectiveness. Respondents rated the technology as very expensive, and a researcher in Qld stated that the technology was of interest, but was still too expensive to be practical (Tables 4.1 and 4.2). A farmer, also from Qld, believed that an automatic weeder called the 'Gator' was of interest, but may not be practical in crops where trickle tape irrigation was used. Several other farmers were keen on automatic weeders, but were likewise concerned about the cost.

None of the farmers we spoke to were using this technology. A large corporate farm is working on developing its own system, although their research is confidential. In Vic, a farmer had seen weed sensor technology at a demonstration day, on a tiller designed to sense and avoid crop plants. However, he did not think the system was effective.

4.4.11. Stale and false seedbeds

A stale seedbed involves preparing the seedbed for planting and then leaving it for between several days and several weeks before planting. During this fallow period, weeds are allowed to germinate, and may even be stimulated through pre-irrigation. Before crop planting, the weeds are controlled with a knock-down herbicide such as glyphosate, paraquat or diquat. Other herbicide options noted by NSW focus group participants included pendimethalin and oxyfluorfen. A farmer in WA works their stale seedbed management in with rain events, rather than pre-irrigating to stimulate weed germination. Weed control in stale seedbeds prior to crop planting is also carried out by fumigation approximately a week before planting (used by a farmer in WA), or by laying plastic mulch in applicable crops (noted by an extension officer in NT).

False seedbeds are similar, although weed control prior to planting is achieved by repeated shallow cultivations and knock-down herbicide applications over several weeks, designed to encourage germination and/or control recently germinated weeds. Farmers using false seedbeds to manage weeds in their paddocks used a mixture of tillage and/or herbicide.

The goal of these approaches is to limit soil disturbance before planting, so that buried seeds do not have the chance to germinate. At the same time, the seed bank in the top layer of soil is reduced through the management of germinating weed cohorts.

Effectiveness and affordability

Stale and false seedbeds appear to result in more effective weed control than crop beds managed by conventional tillage practices alone (Appendix 1, Section 5.12). They rated well for both their effectiveness (relatively effective) and affordability (very affordable) as weed management approaches by survey respondents (Tables 4.1 and 4.2). Sindel *et al.* (2011) found that the techniques were similarly highly rated, but had a low uptake amongst farmers.

SA focus group participants considered stale and false seedbeds to be most relevant and effective in *seeded crops* such as babyleaf spinach and rocket (in the Virginia district), as the managed weed seedbed gives seeded crops extra time to grow above the first post-seeding weed cohort. Several farmers considered the approach to be a very effective way of managing weeds. This included some farmers who had never used a stale or false seedbed before, but were aware of its benefits and were considering adopting the approach in the future. Appropriate timing of the stale seedbed is critical according to a farmer in Tas, to achieve maximum weed suppression within the growing vegetable crop. In NT, a farmer formed their crop beds, applied herbicide two weeks after forming to control the first cohort of weeds, then used a second herbicide application two weeks later to control the second cohort, soon before planting. He considered this false seedbed approach to be highly effective and worth the time spent.

A number of farmers we spoke to in Werribee South, Vic, sought to implement a brief (approximately one week) stale seedbed, where the crop beds were formed and herbicide applied. All farmers who had tried this approach were aware of the benefits, and would have appreciated the opportunity to implement a full one month false seedbed. A farmer in the district extended their stale seedbed period as much as possible by spraying out the previous crop, forming beds, and then waiting a week before applying herbicide prior to planting the next crop. Crop stunting or damage was not reported.

However, for other farmers in Werribee South and elsewhere in Australia, *lack of time* is a major limiting factor for using false seedbeds in particular, as year-round production is commonplace, with no fallow period built into the rotation. A farmer in Werribee South, as well as one in Qld, noted that false seedbeds were not relevant to a year-round production system. Farmers and agronomists in Vic and NSW also considered stale seedbeds to be impractical on farms with highly intensive production. In Werribee South, some farmers attempt to plant their next crop the same day as the previous crop is harvested, leaving no time for time consuming seedbed management between crops. Farmers in this district are often pressured by the need to make a living from a small block, in an area where urbanisation has driven land prices up to the extent that expansion is not practical within the district for most farmers. Farmers in Richmond, NSW, noted similar pressure to produce due to block size, and as such were unable even to consider implementing a brief stale seedbed. Other farmers, such as one in Tas, only used stale or false seedbeds if there was time in the crop cycle.

Other limitations to forming stale or false seedbeds can include soil type ('hard' soils in which beds are ideally formed immediately before planting - noted in Richmond, NSW), or timing of the wet season in NT, which can mean farmers run out of time to plant crops, and must therefore not dedicate time to a stale or false seedbed.

4.4.12. Irrigation management

One farmer in Richmond, NSW, used drip irrigation in their crops rather than flood or spray irrigation to improve their management of weeds. They believed that this approach meant not breaking the pre-emergent herbicide barrier in the wheel tracks, restricted the growth of weeds further in the wheel tracks due to relative lack of moisture, and had other crop management benefits such as being able to traffic the rows sooner. The farmer believed this was an effective way of managing inter-row weeds.

4.4.13. Grazing and slashing

Grazing and slashing appear to be most applicable to organic vegetable farmers, and slashing in particular is commonly used in organic systems (Kristiansen *et al.* 1999; 2007).

Sheep grazing of potato crops after harvest was used in Tas by conventional farmers attending the focus group, to minimise the risk of volunteer potatoes in the subsequent crop. Grazing was considered very effective.

Conventional and organic farmers we consulted in Qld, SA and NT used slashing or burning to manage grass and broadleaf weeds on headlands, along irrigation channels and lines within crop paddocks, and along fencelines. A conventional farmer in the Lockyer Valley in Qld sought to maintain good grass coverage on the headlands, believing that this competition effectively reduced the risk of broadleaf weed refuges establishing alongside the crop rows.

Figure 4.19 Slashing is more commonly used by organic vegetable farmers to manage weeds in areas such as headlands, non-cropping areas and irrigation lines, such as the kikuyu growing in the irrigation lines of this organic farm near Adelaide, SA.

4.4.14. Vertebrate pest control

Farmers in WA and NT believed that pest animals were responsible for spreading weed seeds into vegetable crops (for example, blackberry nightshade berries). Vertebrate pest control was therefore considered an indirect way of restricting the spread of some species, in addition to reducing the damage that these vertebrate pests did to their crops.

4.5. Features of an integrated weed management approach

Integrated weed management (IWM) has been defined as 'a sustainable management system that combines all appropriate weed control options' (Sindel 2000). IWM seeks to minimise the possibility of weed control failure, to reduce the impact of weed management activities on the environment, and to ensure that the mix of techniques used will remain viable into the future (Sindel 2000; Newley and Treverrow 2006; Qld DAFF 2012; Charles 2013). IWM is considered essential to the future of the industry (Sindel *et al.* 2011), however IWM is considered to be fairly poorly developed, with farmers generally relying on a few conventional practices as part of a 'Low or Basic' IWM strategy, such as herbicides, tillage and hand weeding (Thompson 2011). Some examples of IWM used in vegetable production are provided below.

In cucurbit production, Sindel *et al.* (2011) found that the common integrated approach included pre-plant herbicide application, plastic mulch, control of weeds in the inter-row space before the crop vines had spread, chipping or hand weeding within the crop beds, crop rotation, and farm hygiene. An organic cucurbit farmer in NT consulted for this project managed to keep his cucurbit crops almost free of weeds, by combining green manure crops, plastic mulch (including pre-plant solarization) and hand weeding using backpacker staff.

In Werribee South, Vic, where plastic mulch is not used and the main crops include brassicas, celery and lettuce, the common integration of weed control methods will include pre- and post-emergent herbicide application, hand weeding, and cultivation. Use of post-emergent herbicides varies in the district from one farm to the next, and is dependent on crops grown and the willingness of the individual farmer to risk or accept herbicide residue in the soil.

Farmers in the Richmond district in NSW generally combine the following weed control methods as part of their IWM strategy: herbicides (mostly pre-emergent due to lack of post-emergent options); crop and herbicide rotation; hand weeding; and inter-row tillage. Inter-row cultivation is not universally used, and post-emergent herbicides are included where possible. Focus group participants stated that farmer knowledge of the weeds within their crop has a great bearing on the success of their IWM strategy.

In NT, the most important combination of weed methods will vary from crop to crop, but will include tillage, pre- and post-emergent herbicide use, plastic mulch for relevant crops, and green manure crops, which focus group participants considered to be ‘a must’ for the entire production system.

A researcher in SA suggested that IWM should focus on cultural strategies designed to eliminate weed issues over time, including the use of cover crops and living mulches. He believed that cover crops and living mulches had crop growth benefits in addition to their potential to reduce the weed burden.

IWM is an important part of a broader Integrated Pest Management (IPM) strategy within vegetable crops, in which all forms of pests are managed (Thompson 2011; AUSVEG 2012). Weed management both within and surrounding crops is required to reduce the impact of insect pests and diseases on the crop, as weeds often act as a host for important pests and diseases. McDougall (2007) lists current and possible IPM strategies for a variety of vegetable crops grown in Australia. In many cases, management of related or host weeds is recommended to reduce the impact of particular viruses, pests or diseases within the crop (McDougall 2007). Good weed control is important for soil health and management of significant soilborne vegetable pathogens, including *Rhizoctonia* sp., *Schlerotinia* sp., and *Verticillium* sp. (McMichael 2012).

Similarly, soil, water and nutrition management strategies should be incorporated into IWM to foster improved soil health (Wardlaw 2004; Blaesing 2013). While some practices (e.g. crop rotations) may address weed problems as well as soil health issues, other practices may produce conflicting outcomes. For example, reduced tillage may encourage soil borne diseases, while excessive tillage may damage soil structure (Pattison *et al.* 2010). Weeds may be symptomatic of poor soil health, inhibiting the crop's ability to out compete weeds present (Wardlaw 2004). IWM and its relationship to IPM and soil health is discussed further in Appendix 1, Section 5.14.

4.6. Critical factors for weed control success

4.6.1. Weed control methods

Some farmers and agronomists highlighted the importance of particular weed control methods in achieving a high level of weed control success:

- *Herbicides* were important for farmers at different stages of the crop. This included pre-emergent herbicide use as part of effective preparation of crop beds, and post-emergent herbicides within the crop. Farmers succeed when they have access to appropriate herbicides and options, and apply these appropriately (rate, timing and so on). Effective control with herbicides reduces the need for subsequent hand weeding.
- *Bed preparation* was crucial for a number of farmers in providing a weed-free bed at the time of planting or crop emergence. Farmers in Qld and Tas considered bed preparation to involve appropriate cultivation and applying pre-emergent herbicides. Several other farmers highlighted the importance of stale or false seedbeds in preparing a weed-free crop bed through irrigation and then either tilling or spraying germinating weeds.
- For a farmer in SA, effective *tillage* was also vital in minimising the need for hand weeding later in the cropping season.
- *Hand weeding* was crucial for a farmer in Qld, who employed a full time chipper to prevent weeds seeding within the crops. A farmer in SA used a light weight hoe only, to minimise soil disturbance. Although it is costly, hand weeding can be useful when registered post-emergent herbicides are not available and if earlier weed management activities have not been adequate.
- Two farmers, in NT and Qld, sought to manage *weed refuges* such as property or paddock boundaries and irrigation channels. This approach demonstrates the potential value of farm hygiene in reducing weed spread.

4.6.2. Timing

Many farmers mentioned timing as the most crucial factor behind successful weed control. Appropriate timing can be the difference between a weed-free crop and one that is densely infested by the time of harvest (Sindel *et al.* 2011).

Timing relates to the following factors:

- *Weather*, including inaccessibility of paddocks due to rainfall which allows weeds to flourish uncontrolled, the rainfast periods of herbicides, avoiding spray drift during windy conditions, and the need to time methods appropriately during particular seasons.

- *Weed life stage*, including controlling recently germinated weed cohorts through stale or false seedbeds, or ensuring that weeds are controlled before they set seed, managing weeds while they are still small and easy to remove by hand, or managing weeds when they are most susceptible to herbicides.
- *Crop life cycle*, for example controlling weeds one to two weeks before crop planting, or ensuring crop canopy closure will manage weeds.
- *Ground conditions*, especially soil moisture.

4.6.3. Diligence

Several farmers mentioned that diligent application of available weed control methods meant removing weeds before they set seed or spread further, confirming the findings of Sindel *et al.* (2011).

Continual persistence in keeping on top of weeds was crucial to farmers in Tas and Vic, while a farmer in WA emphasised diligence in weed management as being important for removing potential hosts for pests and disease in his crops. A farmer in Qld highlighted the need to control weeds before seed set in harvested crops, so they did caused less problems in the future. A researcher in WA echoed these sentiments, stating that those farmers who are aware of the need to control the seed bank have dramatically reduced their weed management costs over several seasons.

4.6.4. Knowledge and planning

Some farmers suggested that having a good knowledge of their main weeds, their characteristics, and how to manage them through crop rotation and other methods was important to a successful strategy. In this area, agronomists are a vital source of information for most farmers we spoke to.

Several farmers we spoke to have been prepared to carry out independent herbicide research trials on their farm, or to work with researchers in this field. A farmer in Vic with a large operation was prepared to undertake trial and research work in order to arrive at the most effective strategy. A farmer near Darwin, NT, has conducted several years of research leading to a successful strategy for managing nutgrass on his farm. Regular herbicide trials are carried out on a large farm in Tas in an attempt to increase the herbicide spectrum available to them, and manage resistance. A farmer in NSW is independently trialling pre-emergent herbicide alternatives.

4.6.5. Integrated weed management

A farmer in Tas emphasised the importance of IWM in achieving a high level of success in their largely weed free farm. This involved not only synthesising a variety of weed control methods, but using them in a flexible manner.

Whole farm planning for weed management is also crucial. A farmer in Vic listed flexibility of approach (including crop rotation options to address weedy paddocks) and clear communication between staff as important aspects of weed management planning.

5. Research and development

In this chapter we discuss research concepts and ideas suggested in the literature and in consultation with farmers, agronomists, researchers, industry representatives and extension staff for this project. This includes a variety of herbicide and non-herbicide options, many of which are discussed in Chapter 4 in their current form.

Some research and development work currently underway in other agricultural industries, notably broadacre cropping, may be applicable to vegetable production. Project participants in NT believed that there was considerable potential for research in broadacre cropping to be applied to vegetable production, as there was more money available in this industry for applied research. Relevant work in other industries is discussed throughout this chapter.

5.1. Chemical control research

Because herbicide use is widespread in the industry, nearly all farmers, agronomists, researchers and extension staff consulted expressed an opinion on priority areas of research.

There was considerable interest in filling gaps in herbicide availability, determining whether new products were available, streamlining the herbicide registration and minor use permit systems, understanding the extent of herbicide resistance in the industry, and exploring ways to utilise herbicides more efficiently and sustainably. These issues are discussed in the following sub-sections.

A small number of those consulted were interested in further research on fumigation, mainly in the area of application safety (see also Section 6.2.3).

5.1.1. Gaps in herbicide availability

Our industry consultation identified gaps in herbicide availability pertaining to certain crops, weeds, or situations. Where these gaps exist, farmers rely heavily on alternative forms of weed control, which may be considerably more time consuming, difficult and expensive to implement than herbicide application. A gap in availability commonly noted by farmers we spoke to is the relative lack of herbicides available to manage broadleaf weeds in broadleaf vegetable crops, after the crop has germinated or been transplanted. An agronomist in Vic also commented that the current range of herbicides is quite limited, and may be selecting for the dominant weeds now present in Australian vegetable crops. In the next few sub-sections, we discuss crops, weed species and other situations where farmers or agronomists would like more research on herbicide options to be carried out. While these are all *priority areas* in identifying new herbicides for the industry (see Section 5.1.2), we recognise that not all options will be practical to implement.

Lettuce

Lack of post-emergent broadleaf herbicides for use in lettuce production was a common concern raised by farmers and agronomists. As a farmer in Qld commented, lettuce was the most difficult crop to manage effectively for broadleaf weeds within the crop. Focus group participants in Vic considered this issue to be their top research priority. One Vic farmer stated that a herbicide for managing mallow within lettuce crops would be very helpful, while another suggested that a post-emergent for groundsel in lettuce was required. They were aware that some selective products were available for lettuce, but considered them not very effective, and prone to causing lettuce crop damage in their district.

For example, there is a minor use permit for the herbicide phenmedipham, to manage certain weeds in lettuce (see Attachment 1, Table A2). Several farmers relied on this herbicide to manage broadleaf weeds in their lettuce crops. A farmer in Tas felt that it was a very effective option for them, but they would ideally prefer a similar product with a shorter withholding period. While these farmers, at least, appeared to be satisfied with the effectiveness of this herbicide, a researcher in Qld suggested that it was a high risk option for lettuce, with a marginal return on investment. The researcher also suggested that it would be difficult to find an effective post-emergent broadleaf herbicide for lettuce crops, given the amount of unsuccessful research that had been undertaken into this issue internationally over several decades. His opinion on the difficulty in identifying herbicide options was echoed by a farmer in NSW. Farmers in WA had heard of trials in Australia involving mixes of betanal and flumetsulam for post-emergence broadleaf weed control in lettuce, and were interested in more information on these trials.

Brassicas

The literature review (Appendix 1) suggests that post-emergent herbicides for use in brassica crops are not available, so that farmers rely heavily on cultivation and hand weeding. This was confirmed during the field research. A farmer in Vic considered that a post-emergent herbicide for use in broccoli and other brassicas would be very helpful – an equivalent to prometryn which he used successfully in his celery crops.

In SA, agronomists noted that a minor use permit was in effect for the herbicide clopyralid to manage some broadleaf weeds in cauliflower in WA (see also Attachment 1, Table A2). They wondered whether this product could be used more widely across Australia in brassica crops.

Cucurbits

Focus group attendees and farmers in NT believed that more pre-emergent herbicide options were required for cucurbit production, as well as selective herbicides for use within the crop, even if spot spraying was required. A farmer in Qld wanted to see post-emergent options for cucurbits developed, arguing that the only current option, clomazone, was too volatile. A researcher in Vic suggested that selective herbicides to control paddy melon (*Cucumis myriocaropus*) were required, as the only current alternative was to use a 12 month fallow.

Other crops

- A farmer in NT found that s-metolachlor does not work well on broadleaf weeds within his basil crop, and damages the crop plants.
- Agronomists in SA noted that linuron is currently used in parsley crops, but that over-reliance on this herbicide was a concern. They suggested pendimethalin as a possible alternative.
- Also in SA, agronomists noted that a minor use permit existed for cyanazine in onions in Tas, and that perhaps research was needed to determine its potential in regions with sandy soils such as Virginia in SA.
- Farmers in WA suggested that the herbicide dimethenamid-p may be useful for nutgrass control in onion crops, and was worth further research and trial activity.
- Also in WA, farmers noted that alternative pre-emergent or selective herbicides were required to manage resistant ryegrass within carrot crops.
- An extension officer in NT noted the lack of pre-emergent options in the specialty crops okra, snake bean, and Asian melons.
- Farmers and agronomists in SA and NSW noted a lack of herbicide options for minor crops.

Weed seed management

In Werribee South, Vic, farmers were interested in herbicide chemistry that was effective in sterilising weed seed while it was still on the surface, before it had a chance to germinate. They believed that such products would be most applicable directly after crop harvest. The farmers noted that fumigation achieves something similar, but that it is very expensive and unsafe, and so is rarely used in the district. The farmers were strongly in favour of any way to break down or reduce the weed seed bank, and considered this a top research priority.

Specific herbicide options and alternatives

Farmers and agronomists requested research into a variety of specific herbicide options (see also Section 5.1.2). They recognised that these options would be difficult to obtain, but considered their potential availability to be very useful:

- A farmer in Vic would like a less toxic pre-emergent herbicide alternative to oxyfluorfen, with a longer window of opportunity to use.
- A farmer in WA suggested that alternative non-residual knockdown herbicides to glyphosate were required. A farmer in Vic similarly wanted

alternatives to glyphosate, but in his case there was concern over glyphosate residues and its possible impact on subsequent crops.

- An organic farmer in NT wished to see research into selective viruses that may be applied to weeds, as well as organic bioherbicide alternatives.

Herbicide control in adjoining non-cropping areas

SA focus group participants suggested that residual herbicide alternatives for use around sheds, glasshouses, and other farm infrastructure were required – products which work longer than the glyphosate and paraquat/diquat, both of which are commonly used. Having such products available would facilitate more effective farm hygiene.

5.1.2. New herbicides

Additional herbicide options would give vegetable farmers greater flexibility in their weed control program, and may extend the useful life of the limited range of herbicides currently available, by providing rotation options.

However, little work has been completed on entirely new herbicides for use within Australian vegetable crops in recent years. A HAL staff member noted that there was very little new chemistry being introduced, or likely to be introduced in the future. The most recent activity seems to have been research that led to the successful registration of clomazone for a limited range of vegetable crops by Peracto. Other recent research has focused on high risk options for major crops. Since then, much of the work has centred on usage refinement of existing herbicide options (such as new formulations), or legalisation of use that may have already been common practice (under a minor use permit). Overall, those involved in research and registration of herbicides in the vegetable industry could see that new herbicides were a priority, but that there were few feasible options due to the small and fragmented nature of the market, and trial and registration costs.

Registration of new herbicides for vegetable cropping is a difficult undertaking, and may not be practical in many cases. Herbicide registration is discussed in more detail in Section 5.1.3. Nonetheless, our discussion with farmers, agronomists, and herbicide resellers identified several herbicide options which these stakeholders believe may have some potential for use in vegetable production.

We have conducted a limited search of herbicide options used in the United States. There appear to be a wider range of products registered there than in Australia. More detailed follow-up research into herbicides registered for vegetable crops in the US, Europe and elsewhere, may identify new options for consideration in Australia. Many farmers and agronomists we spoke to during this project considered that it was worth looking into herbicides already used in vegetable crops overseas.

Potential herbicide options identified during stakeholder consultation and international research are listed below in Table 5.1. These herbicides are discussed in more detail in the following sub-sections.

Table 5.1 Potential herbicide options for Australian vegetable production

Chemical Active Ingredient *(Name)*	**Distributor**
Bensulide *(Prefar)*	Gowan Company (USA)
Chloridazon *(Pyramin)*	BASF (Australia)
Ethalfluralin *(Curbit)*	Loveland Products (USA)
Flumetsulam *(Broadstrike)*	Dow AgroSciences (Australia)
Haloxyfop *(Verdict)*	Dow AgroSciences (Australia)
Mesitrione *(Callisto)*	Syngenta (USA)
Metoxuron *(Carrotex)*	*Unknown (Discontinued)*
Prosulfocarb *(Defy)*	Syngenta (USA)
Prosulfocarb/S-Metolachlor *(Boxer Gold)*	Syngenta (Australia)
Pyroxasulfone *(Sakura)*	Bayer CropScience (Australia)
S-Metolachlor *(Dual Gold)*	Syngenta (Australia)
Tembotrione *(Laudis)*	Bayer CropScience (USA)
Terbacil *(Sinbar)*	AgNova (Australia)
Unknown new herbicide	Syngenta (Australia)

Bensulide (Prefar)

This pre-plant or pre-emergent control herbicide is registered in the US for management of selected broadleaf and grass weeds in onions, garlic, shallots, certain leafy vegetables, cole crops, fruiting vegetables, and cucurbits Weeds controlled include fat hen, pigweed, and nettles.

We were unable to identify an Australian distributor for this product by internet search, however it is mentioned in Australian weed resistance literature pertaining to broadacre crops. In the US, bensulide is distributed by the Gowan Company.

Chloridazon (Pyramin)

This is a pre-emergent broadleaf and grass control herbicide currently registered in Australia for use in beetroot, silver beet and fodder beet, and is distributed by BASF.

BASF staff suggested that this herbicide had potential for use in other beet crops.

Ethalfluralin (Curbit)

This herbicide is registered in the US to control annual grasses and broadleaf weeds in cucurbit crops. There is currently no Australian distributor, however it is distributed in the US by Loveland Products.

Sindel *et al.* (2011) suggested this herbicide was worth looking at for potential registration in Australia.

Flumetsulam (Broadstrike)

This pre- and post-emergent broadleaf control herbicide is currently registered in Australia for use in various cereal and seed crops, and pastures. Weeds controlled include shepherd's purse, wild turnip, capeweed, wild radish, fat hen, fumitory, wireweed, marshmallow, caltrop, and chickweed. It is distributed in Australia by Dow AgroSciences.

Dow AgroSciences staff did not mention this herbicide to us as an option for vegetable crop production. In addition to the phenmedipham/flumetsulam trial activity mentioned by WA farmers, a farmer in Qld suggested it may be an option in vegetable crops, and believed it was used to control fat hen in vegetable crops in the US. However, this farmer also believed that residue problems with the herbicide meant that registration in Australia may be difficult to achieve.

Haloxyfop (Verdict)

This post-emergent herbicide for selective grass control in various broadacre and fruit crops is distributed in Australia by Dow AgroSciences.

This herbicide was mentioned in Sindel *et al.* (2011) as a possibility for use in cucurbit crops, but at the time further trial work was not suggested by the Dow AgroSciences representative.

Mesotrione (Callisto)

A pre- and post-emergence herbicide for controlling broadleaf weeds in corn. The product is currently available in the US but not in Australia, and is available from Syngenta.

Metoxuron (Carrotex)

Farmers and agronomists from SA, WA and Tas mentioned that this herbicide used to be registered in Australia, and was effective in controlling cleavers and volunteer potatoes in carrot and potato crops. They believed it was still available in the UK.

However, internet research suggests it has been deregistered in Australia and in the UK, and a distributor could not be identified. Reregistration of metoxuron was considered unlikely in Australia (Frost 2004).

Prosulfocarb (Defy)

This herbicide is registered in the UK to manage a range of broadleaf weeds, including cleavers, in potato crops. It is distributed by Syngenta and is not available in Australia currently, though prosulfocarb/s-metolachlor is (see next section).

Prosulfocarb was mentioned as a desirable herbicide option by participants in the Tas focus group, given the growing problem they were experiencing with cleavers in the potato and other vegetable crops.

Prosulfocarb/S-Metolachlor (Boxer Gold)

This is a pre-emergent herbicide currently registered in Australia to control annual ryegrass, other grasses and broadleaf weeds in barley and wheat. It is distributed in Australia by Syngenta.

Syngenta representatives advised that this herbicide has already been trialled in onion, carrot and tomato crops for control of broadleaf and grass weeds. Further research in tomatoes was not considered worthwhile, though the herbicide showed good potential within onion and carrot crops, and warrants further development in the opinion of Syngenta staff.

We were advised, however, that Syngenta would require considerable industry funding support to proceed with trial and registration activity.

Pyroxasulfone (Sakura)

This pre-emergent herbicide for grass control (including resistant ryegrass) is distributed in Australia by Bayer CropScience, and is registered for use in wheat and triticale.

Bayer CropScience staff advised us that this may be an option worth exploring for use as a pre-plant grass management option in vegetable crops. However they acknowledged that there would probably be minimal demand for such a product from vegetable farmers, given that there are already several registered herbicide options for grass management.

S-Metolachlor (Dual Gold)

This herbicide is already registered in Australia for broadleaf weed control in brassicas, beans and sweet potatoes (Attachment 1, Table A1). Sindel *et al.* (2011) found that it was registered in the US for cucurbit crops. Agronomists in SA confirmed that this herbicide showed potential in cucurbit crops such as cucumber, with off-label trials also having been conducted with some success in pumpkins.

Tembotrione (Laudis)

This herbicide is registered in the US for post-emergence control of grass and broadleaf weeds in corn. The product is distributed by Bayer CropScience in the US, but is not currently available in Australia. Weeds controlled include chickweed, potato weed, fat hen, blackberry nightshade, pigweed, and shepherd's purse.

A farmer in Qld mentioned that this herbicide would be a useful addition for Australian farmers.

Terbacil (Sinbar)

Terbacil is used to selectively control weeds in a number of fruit crops, as well as in lucerne. It is distributed in Australia by AgNova.

Sindel *et al.* (2011) found that this may be an option worthy of further exploration for selective control of broadleaf weeds in cucurbit crops.

Unknown herbicide (Syngenta)

Syngenta representatives advised us that another herbicide is currently being explored for use in broadacre cropping in Australia, but were unable to release confidential details at this stage.

At the time of writing, Syngenta broadacre portfolio staff were determining whether the herbicide warranted development for broadacre cropping. If it is registered for this larger market, Syngenta staff suggested it may be developed further for registration in certain vegetable crops.

5.1.3. Herbicide registration

There appear to be several herbicides with potential to use in vegetable crops. However, a researcher in Qld suggested that new herbicides are unlikely to be introduced to Australia simply for use in vegetable production, because of the small size of the vegetable production market, its fragmentation into a large variety of crops, and the cost of trial and registration work (see also Sindel *et al.* 2011). Herbicide manufacturer representatives suggested that these have been ongoing issues in bringing new chemistry to Australia for vegetables.

The small Australian market means that new options will most likely have to come from herbicides that have been registered in Australia for use in broadacre crops or other uses. However, if herbicides that have been available for other uses in Australia for some time are not already registered for use in vegetables, there may be a good reason for this (such as phytotoxicity risk or persistence), so they are unlikely to be registered in the future.

Focus group participants in Vic felt it was worth exploring the possibility of ‘worldwide registrations’ for herbicides, to avoid duplication of trial and research work currently undertaken in several different countries for the same herbicide in the same crops. Similarly, several farmers and agronomists around Australia also suggested that herbicide trial data from other parts of the world, particularly those with similar climates to Australia's key vegetable regions such as South Africa and Brazil, could be included in APVMA consideration of new herbicide options.

This may save duplication of research, and make funding new herbicide registrations more feasible. Currently, participants felt that APVMA and government red tape was a major stumbling block to achieving new herbicide registration. One agronomist in Tas noted that this could be considered a 'low hanging fruit' research and development issue for the Australian industry. However, the potential environmental impact of new herbicides and requirement for specific local data, may add significantly to the cost of trial activity for new options, making trial work cost prohibitive.

To alleviate the high cost of herbicide trial and registration, project participants suggested that HAL work closely with herbicide manufacturers, researchers, the APVMA and farmers in exploring options. Farmers in WA, for example, were happy to work with the APVMA on herbicide trials, and a number of farmers we spoke to were already carrying out trial work, either alone or working with researchers. NT focus group attendees believed that the time taken to register new herbicides is caused by herbicide manufacturers having to spend large amounts of money on associated research and trial work, while only hoping to profit from a relatively small Australian market. Industry support, including funding and research support, may speed up this process (see also Sindel *et al.* 2011). A researcher in Vic believed that joint funding of herbicide trials was required, involving herbicide manufacturers, farmers and the tax payer. According to a researcher in WA, trial activity should focus on the whole farm system, rather than focus purely on herbicides.

A more recent factor influencing herbicide registration has been growing knowledge of their potentially serious environmental impacts. For example, a herbicide company representative noted that selective broadleaf herbicides have been identified as a major cause of algae destruction in the Great Barrier Reef, and that as a result achieving registration is more difficult. He considered that registration specifically for southern Australia will still be difficult, as there was potential for damaging herbicides to be used off-label in northern Qld.

5.1.4. Minor use permits

Several research participants were grateful for the minor use permit system, as it opened up the possibility of using unregistered herbicides that have proven to work effectively in vegetable crops. However, they did state that even minor use permits require efficacy and residue data, which can be difficult and potentially costly for a farmer and/or agronomist to arrange. The participants suggested that the industry needed to fund trial sites for minor use data gathering, and that some levy funds could be spent in this area. Several farmers and agronomists also suggested that minor use permits restricted to some states needed to be made available more widely.

Nonetheless, awareness of how the minor use permit system works appeared to be fairly poor amongst farmers. This is discussed further in Section 6.2.3.

5.1.5. Herbicide resistance

Some weed resistance to herbicides registered for use in vegetable crops has been identified in the literature. This appears likely to become a bigger issue in the future as resistance has also been noted outside Australia (Appendix 1, Section 6.1.1). Farmers need to be especially aware of the potential for resistance to selective herbicides to develop in grass weed species. Herbicide resistance research is well advanced in the Australian grains and cotton industries, and the vegetable industry may benefit from these findings (Appendix 1, Section 8.3).

Several farmers and others in the industry were either deeply concerned about the development of herbicide resistance amongst major weeds of vegetables, or had noted examples of its possible occurrence on their farm. A researcher in SA suggested that weed resistance be mapped using GPS technology to track herbicide resistance in the industry, as has been carried out in broadacre cropping.

Glyphosate resistance is a major concern not only in vegetable production but in other forms of horticulture and agriculture. In NT, a farmer noted that developing glyphosate resistance was probably due to lack of knowledge about its correct use amongst some farmers. In Tas, a farmer had glyphosate-resistant ryegrass on their farm, and was already conducting on-farm trials in collaboration with researchers.

Some farmers were concerned about growing weed resistance to other herbicides commonly used in vegetable production. In Qld, a farmer felt that clover (*Trifolium* spp.) was becoming resistant to pendimethalin on his farm, and this was a concern as it was the main form of clover control in his lettuce crops. He also felt that chickweed and carrot weed (*Daucus carota*) were becoming resistant to pendimethalin. He and another farmer from Qld suggested that alternative herbicides to pendimethalin were required. Similarly, an agronomist in NSW was concerned about resistance to s-metolachlor developing. Farmers in Werribee South, Vic, were concerned that a number of their major herbicide options were becoming less effective, and that resistance may be developing. One farmer in this district suggested that reduced effectiveness may be due to non-resistance factors such as rising sodium in the soil, or changes to soil biology.

A farmer in SA considered that research into how effective current herbicide options are on weeds was worth considering. More research may be necessary to survey and test for weed resistance within vegetable crops across Australia. This research could identify which herbicides are becoming less useful as a result of resistance, and which herbicide or non-herbicide management alternatives may provide economic alternatives. Much of the herbicide resistance work already carried out in Australian grains and cotton production will also be of relevance in vegetables, particularly where the work covers weed species and herbicides that are features of vegetable production. Another farmer in NT suggested that a weed resistance testing service for farmers was an option worth considering. A farmer in NSW was having to make a greater number of herbicide applications than previously, and was concerned not only about resistance but rising herbicide costs. He wished to know which herbicides were less effective due to resistance, so that he could explore alternatives.

5.1.6. Correct herbicide usage and fine tuning

Several farmers and other experts noted that the risk of herbicide resistance (or reduced effectiveness) was exacerbated by incorrect use of the limited number of herbicides available to vegetable farmers. This included:

- Inappropriate herbicide mixes and lack of knowledge about what happens when herbicides are mixed.
- Incorrect or inappropriate use and selection of sprayers, nozzles, volumes and pressures.
- Failure to observe correct label use, or to ensure sensible use within label requirements, possibly using lower rates where these are still effective. Focus group participants in Tas believed it was vital to educate farmers across Australia on the importance of following the herbicide label, but that the number of non-English speaking farmers may be a barrier here.
- Over-reliance on the same herbicides, when rotations were available. This issue may be related to the relative cost of the rotation options.

Some also noted that fine tuning the use of currently available herbicides could lengthen their useful life, and was preferable to researching new options that may never come to fruition. Farmers considered that improvements to current herbicide use could be made in the areas of application timing, considering the appropriateness of herbicides on particular soil types, appropriate use of fertiliser, and proper application (nozzle usage and rates) to minimise weed regrowth. A researcher in Qld is currently undertaking trial work on variable herbicide rates.

Farmers in Qld and WA were interested in further research into plant-back periods or withholding periods, to determine whether the currently labelled periods were appropriate. In WA, farmers gave specific examples:

- The herbicide linuron, which previously had a withholding period of 49 days, but was difficult to use in carrot crops with its current, longer withholding period of 70 days.
- The withholding period for grass controlling herbicides in lettuce is four weeks, whereas in other crops the withholding period for these same herbicides was two weeks. Farmers wondered whether the four week withholding period was really required in lettuce.

Similarly, farmers and agronomists in Tas thought that herbicide labels in general may need to be revisited to ensure that appropriate, sustainable use is being recommended. Agronomists in SA felt that labels needed to include information on herbicide efficacy and dilutions, and herbicide rotation strategies.

Agronomists will generally be aware of these issues, but may not have the opportunity to pass this information on to all their vegetable farming clients.

In summary, farmers need to be made aware not only of instances of herbicide resistance in the industry, but also of correct herbicide usage, and integration with other techniques. In this way, over-reliance on a limited range of herbicides may be reduced, and resistance is less likely to develop. As a farmer in NT commented, 'killing weeds properly means that no resistance will develop'.

5.2. Non-chemical control research

5.2.1. Tillage

Several farmers and researchers noted that advances in tillage technology and techniques were worth exploring for their potential in vegetable cropping. These included:

- The 'Weedfix' cultivator for intra-row tillage (Figure 4.9).
- An in-crop mulcher called 'WeedSmasher', which a researcher felt might be useful in mulching weeds and incorporating them into the soil as a green manure before seed set.
- Direct drilling of vegetable crop seeds and green manure crops to limit soil disturbance, a strategy now adopted by over 90 per cent of broadacre farmers in most regions. Though farmers noted that this type of low-till system would be difficult to achieve in vegetable cropping (see also Appendix 1, Section 8.1).
- A 'sweep cultivator' seen online by a farmer in Qld.

5.2.2. Biodegradable mulch film

The literature suggests that the quality of biodegradable mulch films continues to improve. These mulches are also becoming more cost-effective relative to the conventional plastic mulch alternatives, though many farmers are still sceptical of their potential (Section 4.3.2). Continued research is needed on this technology to improve its effectiveness further, as it has the potential to replace conventional plastic mulch film with relatively little outlay on new equipment for farmers. It can also significantly reduce the environmental impact of vegetable growing, and make it easier for farmers to manage their paddocks post-harvest: mulch retrieval will no longer be necessary if it is designed to break down in place after harvest (see Appendix 1, Sections 5.4.1 and 6.3).

Several farmers expressed an interest in using biodegradable mulch films in their crops, if their performance could be improved. Areas that needed more research according to farmers and researchers include: ensuring the product lasted through the life of the crop; ensuring it was practical in different climates around Australia; and understanding what happens to the mulch pieces as the mulch film breaks down.

Biodegradable mulch films appear to be a much more promising mulch alternative for farmers than the various organic mulch options discussed in the literature review (Appendix 1, Section 5.6), although farmers in Qld and Tas interested in the potential of spray-applied paper-based mulches, such as used on roadside cuttings, to be used within vegetable crop beds.

5.2.3. Green manures and cover crop mulches

Farmers were interested in research to determine the impact of non-biofumigant green manure crops on weed growth in the paddock. Some believed these crops reduced weed numbers, while others believed they made the problem worse. It is likely to depend on the type of green manure crop and the weeds present. In NT, a farmer suggested that weeds themselves might act as a green manure crop if ploughed into the soil before setting seed, and that the nutrients in weeds might be worth analysing for their green manure potential.

Within the crop, green manure 'cover crop' mulches are less effective than plastic mulch for weed control. The longer-term viability of these systems is still dependent on further research that may refine their ability to control weeds more effectively. Their viability may also depend on the comparative longer-term viability of plastic or biodegradable mulch films. If biodegradable mulch films develop to the extent that they become a practical replacement for conventional plastic, they will most likely become a mainstay of production in crops where plastic is currently used. In 'killed' cover crop mulches, research is required to overcome poor soil contact with the root ball of the crop during planting, and to address nutrient tie-up and allelopathy impacts on the crop. An extension officer in WA suggested that grasses may be sown as a cover crop mulch, controlled using a non-selective herbicide, and crops such as carrots sown into the resulting killed mulch.

In addition to cover crops for the paddocks themselves, farmers and extension staff in SA expressed an interest in perennial shrub coverage in non-cropping areas, such as near sheds and along permanent irrigation lines. The goal of this coverage would be to out-compete weeds while also providing biodiversity for beneficial insects. According to an extension officer in SA, SARDI has already been carrying out research in this area.

5.2.4. Biofumigation

Several farmers and researchers believed that more research should be carried on the specific impact of biofumigant crop options on weeds. Participants in the Tas and SA focus groups considered biofumigant crop research to be a high industry priority. They pointed out that several seemingly effective biofumigant varieties are now available. Suggested areas of research included:

- Determining the best performing biofumigant crops for weed suppression (in terms of competition from the biofumigant crop, and fumigation impact within the soil).

- Determining which weeds are more susceptible to biofumigation (with a specific focus on weeds of concern in Tas, such as glyphosate resistant ryegrass, cleavers, and oxalis).
- Understanding the cost effectiveness of biofumigants as a rotation for the main vegetable crops.
- Determining the most effective way to incorporate biofumigant crops into the soil.

An agronomist in Tas had seen preliminary data which showed that biofumigation using the mustard variety 'Caliente' had a significant impact on the weed seed bank in cropping soils, if mulched and incorporated quickly. A farmer in Tas had been using this biofumigant crop for several years, and believed it was having a marked effect on the emergence and vigour of ryegrass in his paddocks. Project participants from Tas, SA and WA believed that biofumigation potentially offered a realistic supplementary option to herbicides and fumigation.

5.2.5. Chipping and hand weeding

Improvements to hand weeding implements and techniques may allow for more efficient hand weeding within vegetable crops, Since this is such a significant cost to many vegetable farmers, any improvement will have significant industry-wide benefits. Farmers are generally reticent to use hand weeding except as a last resort. As a farmer in NSW pointed out, not only do farmers not want to use hand weeding, but it is also hard to find people willing to work as chippers. The farmer therefore believed that research in hand weeding was not warranted. However, we have noted that most farmers are forced to rely on hand weeding, despite its high cost (Section 4.2.1). Related research in this area is worth carrying out, as it is 'low-tech' – relatively cheap, easy to implement – and can potentially be a high return on investment.

5.2.6. Crop rotation

The literature (Appendix 1) suggests that more research is needed on the potential benefits of crop rotation as a weed management tool. This would include the ability of different crops to out-compete specific weeds in the field, and the potential for rotations to provide access to a wider range of weed management techniques, particularly for the use of different selective herbicide options. Beneficial crop rotation options, according to an extension officer in SA, include can include non-vegetable crops such as green manures and biofumigants (Sections 4.4.3, 4.4.4, 5.2.3 and 5.2.4), and production crops (such as hay), reducing reliance on particular herbicides, and improving soil quality.

A farmer in Vic noted that crop rotations, where he was able to apply them, worked very well as a weed management approach. However, the results are often not easy to generalise. Crop rotation may benefit pest, disease and weed management as well as soil health, though the benefits will be very site and crop-specific, and specific management will be needed. As such, the SA extension officer noted that crop rotation options, costs and benefits might be included in a crop protection decision support tool (see Section 5.3.2).

5.2.7. Permanent beds, controlled traffic farming and precision agriculture

Farmers in other cropping industries have moved away from tillage to a much greater extent than vegetable farmers (Appendix 1, Section 8.1). Most farmers we consulted with were sceptical about the feasibility of implementing a permanent or semi-permanent bed system with reduced tillage in vegetable production, though we did discuss semi-permanent beds and killed mulch trials with an organic farmer in Qld (Section 4.4.3). A commonly voiced concern about the feasibility of permanent beds was the additional reliance the approach places on non-selective herbicides, which are already showing additional signs of resistance in industries where reduced tillage has been commonplace for several years.

Controlled traffic farming, generally operating in a permanent or semi-permanent bed system and utilising precision guidance technology, has a range of clear environmental and farm management benefits, including improved weed management by reducing weed seed stimulation. Some farmers and researchers noted that precision guidance technology might facilitate permanent bed systems, controlled traffic farming, and more efficient crop coverage of the paddocks. However, farmers in Tas noted that the current GPS guidance technology was less effective in undulating landscapes (Section 4.4.9), and believed that this required more research. A farmer in WA had also trialled zero-till vegetable cropping without success (see also Appendix 1, Section 8.1).

Precision weed detection and herbicide application technology is also under development. The literature in this area (Appendix 1, Section 8.3), as well as the advice of several farmers over the course of this project, suggests that precision technology is still largely the preserve of broadacre cropping, and has given broadacre farmers significant production advantages. It has the potential to reduce the farmer's reliance on hand weeding, reduce herbicide use through targeted application, and increase crop yields (Appendix 1, Section 8.3). A number of farmers indicated their interest in precision weeding, either using herbicides (spot spraying, wick wiping or drop application) or precision manual weeding implements. A farmer in Tas considered targeted, non-selective herbicide application potentially beneficial, by removing herbicide withholding periods from the equation.

Several farmers and researchers were aware of the robotic weeder under development at the University of Sydney[1], and believed that research activity should continue in this area. A researcher in Tas believed that this technology could eventually become advanced enough to allow weeds to be managed mechanically, rather than relying on herbicides.

[1] http://www.acfr.usyd.edu.au/research/agriculture.shtml, accessed 24/7/14.

Our review of the literature, and the observation of several participants in this project, highlighted that precision guidance and control technology is more advanced in broadacre cropping than in horticulture, and that the vegetable industry may be able to benefit from a number of advances:

- monitoring technology for weeds, disease and yield;
- robotic technologies developed for weeding and harvest in fruit (strawberry) production and broadacre cropping;
- weed sensor technology (see also Section 4.4.10) such as 'WeedSeeker'; and
- drone technology for surveillance, weed mapping and control (ground and aerial-based).

However, it is likely that precision agriculture will need to become more effective and affordable before vegetable farmers consider it a worthwhile investment. Farmers and agronomists in NSW believed that this technology was a long way from being viable on relatively small-scale vegetable farms, and was most likely to be relevant for larger corporate vegetable farms, or broadacre cropping. Some farmers responding to the survey showed an interest in precision agriculture, however a larger number were unsure if it would be useful to them.

More work is therefore required to determine whether precision guidance technology, weed detection and control is applicable in smaller scale vegetable farming in different parts of Australia.

5.2.8. Thermal weed control

Organic farmers consulted during this project were interested in more research on a variety of thermal weed management options, including flaming, steam weeding and banded steam weeding, and steam 'fumigation' for non-residual reduction of the weed seed bed. However, the consensus amongst some organic and conventional farmers who discussed thermal weeding approaches, was that it is too expensive to be a viable option. Farmers in WA noted that while steam weeding is used more extensively in Europe, it is also very slow and mostly considered for very high value crops such as cut flowers. An Agronomist in Tas believed that thermal weeding was too intensive in its use of fossil fuels, to the extent that he believed efficient herbicide use had a smaller environmental impact than the thermal alternatives.

5.2.9. Solarization

Australian researchers consider that solarization is probably not economic in Australia (Appendix 1, Section 5.13.3; see also Section 4.4.1). Nonetheless, some farmers were interested in research to demonstrate the effectiveness of solarization. In Tas, a farmer was using solarization (under black plastic or biodegradable mulch) in his paddocks. He surmised that this had halved the weed seed bank within his crop rows, but was interested in research to quantify its true effectiveness. Farmers in WA adopt a 'solarization' method without plastic mulch in the summer fallow period (Section 4.4.1). They were interested in cost-benefit analysis on this approach, as well as solarization using plastic, and in extension of the findings to the industry if the approach proved cost-effective.

5.2.10. Stale and false seedbeds

This research, and prior work completed by Sindel *et al.* (2011) suggests that stale and false seedbeds are both effective and affordable options for weed control, but that there is relatively low uptake amongst farmers. One reason for this low uptake identified in this project is lack of time in regions where production is continuous, and where fallow or non-cropping periods are therefore relatively rare (see also Section 5.6.2). As a farmer in Vic stated, stale or false seedbeds are not practical in districts where farmers must grow three to four crops each season.

Because farmers in the Werribee district in Vic do not have time to institute a conventional stale or false seedbed, they believed it was important to research ways of promoting weed seed germination more quickly than through pre-irrigation or pre-tillage, and following up on this rapid germination with a knockout herbicide application. This approach might also be relevant to farmers in Richmond in NSW, where similarly intensive production takes place. Focus group participants in NT also sought ways to stimulate weed seed so that all seeds germinate simultaneously, requiring only one pre-plant control using either herbicides or tillage.

5.2.11. Weed seed bank

According to research participants, managing the weed seed bank more effectively means understanding the ecology of weeds, as well as the best way to manage them *before they set seed*. A farmer in Vic believed it was important to understand more about the factors, or conditions, that affect weed germination, as the interplay of these factors may help the farmer decide whether or not to apply herbicide. These factors include air and soil temperature and moisture, nutrient levels, climate, and wind.

Farmers and agronomists from Vic, NT and Tas wanted to know more about the effectiveness of a range of methods that may manage weeds before they set seed. These included: herbicide; tillage; stale and false seedbeds; humic acids; crop rotation; IWM, and fallow management (Section 5.2.15). Focus group participants in Tas believed that non-fumigant products designed to sterilise weed seeds were potentially useful (see for example biofumigation, Section 4.4.4).

5.2.12. Biological control

Some biological agents have been released in Australia to help manage weeds of relevance to vegetable production (Figure 5.1). For farmers, 'biological control' covers the spectrum from viruses to grazing animals. In NT, a farmer wanted more research on the potential of nematodes and fungi to manage weeds. As with most biological control programs, the farmer acknowledged that this would require agents that specifically target certain weeds, without impacting the crop or non-target plant species. Farmers in SA and Vic saw a need to introduce biological control agents for specific weeds of importance in vegetable crops, to reduce farmer reliance on herbicides. The farmer in SA pointed to the successful management of salvation Jane (*Echium plantagineum*) in his state, as an example of what may be achievable for some weeds of vegetable production.

Some organic and conventional farmers considered grazing animals (Sections 0 and 5.2.15) a form of biological control of weeds in vegetable paddocks, and were interested in concepts such as Dorper sheep that could be used for weed management without having to be shorn, and using free range poultry to reduce the weed seed bank in recently harvested paddocks.

5.2.13. Genetic modification

Glyphosate-tolerant crop varieties are now available for a number of broadacre crops (Appendix 1, Section 8.2). Several farmers were interested in glyphosate-tolerant vegetable varieties given the lack of in-crop selective herbicide options for weed management, particularly of broadleaf weeds. A farmer in Qld was also interested in crop seed treatments, to reduce the susceptibility of crop seed to pre-emergent herbicides. However, more research would need to be completed regarding the willingness of farmers to rely more heavily on glyphosate or other widely used herbicides, and the willingness of the community to purchase vegetables grown from GM plants.

A HAL staff member suggested that glyphosate-tolerant vegetable crops were unlikely ever to be developed, believing that similar broadacre cropping varieties had resulted in such heavy reliance on this herbicide, that cases of weed resistance were increasing rapidly. Glyphosate use within a tolerant crop is recommended within these industries as only part of an IWM approach (Appendix 1, Section 8.2). However, because the likely outcome was accelerated herbicide resistance in vegetable production, the HAL staff member argued that this investment potential was better diverted to improving non-herbicide weed management. Furthermore, farmers in WA noted that they are currently banned from using genetic modification technology in vegetable production.

Figure 5.1 Calligrapha pantera*, released in NT as a biological control of the weed* Sida acuta*.*

5.2.14. Irrigation management

We discussed irrigation management with a farmer in NSW, who was employing drip irrigation to reduce the weed burden within the inter-row space in their vegetable paddocks (Section 4.4.12). This farmer believed that more research could be conducted in this area to implement drip irrigation even more effectively as a weed management tool, rather than farmers relying on 'trial and error' in putting such a system in place (Figure 5.2 to Figure 5.4).

An extension officer in SA advised us that biodegradable irrigation 'trickle tape' has recently become available in Australia from 'One World Environmental Solutions' (www.beyondgarbage.com.au). The extension officer suggested that this be considered in combination with biodegradable plastic mulch, or indeed other crops in which time savings are beneficial by not having to retrieve trickle tape after harvest.

Some farmers are using shielded herbicide sprayers or slashing to manage weeds in the permanent irrigation lines in the paddocks. Perennial shrubs have been suggested as a weed suppression option in these lines, and some work has been carried out in SA (Section 5.2.3). However, other options suggested by farmers include plastic mulch or concrete. An organic farmer in SA was interested in whether an automated, tractor-mounted slasher/whipper snipper could be used for this purpose, having observed such technology overseas in tree horticulture.

Figure 5.2 Sophisticated overhead irrigation near Gingin, WA.

Figure 5.3 Spray irrigation near Werribee, Vic.

Figure 5.4 A farmer near Richmond, NSW, was experimenting with trickle irrigation to limit the moisture available for weed growth in between the crop rows.

5.2.15. Harvest, post-harvest and fallow management

Managing weeds effectively during crop fallow periods (where such periods are incorporated in the crop cycle) is vital as it can reduce the seed bank over time (Section 5.2.11), and therefore the impact of weeds within the following crop. Management options may include non-selective herbicide application (Section 4.1.5), biofumigant and green manure crops (Sections 4.4.3 and 4.4.4), and grazing (Section 4.4.13).

Focus group participants in Tas were interested in options to minimise the number of weeds setting seed at the time of harvest (pre-plant or in-crop weed management), as well as after harvest. A post-harvest management option used in some potato crops in Tas is to graze the paddocks with sheep, however the true impact of this approach is not understood well, and requires research (see also Section 5.2.12). A farmer in WA occasionally grazed cattle in his vegetable paddocks during the fallow period, but was unsure of the weed management benefits. Farmers and agronomists in Tas also wanted to see more work completed on ways to reduce the spread of weed seeds during harvesting activities. The overall goal is to reduce viable seed produced in vegetable paddocks throughout the year. In SA, research and extension staff believed that fallow cover crops had a vital role in out-competing weeds, in addition to other potential benefits such as soil fumigation (Section 4.4.4).

5.3. Improving weed management efficiency

5.3.1. Integrated weed management

IWM appears to be fairly poorly developed on most Australian vegetable farms, with farmers focusing most of their attention on the management of pests, diseases and viruses in their vegetable crops, and perhaps not considering the links between weed and pest impact and management (Thompson 2011). However, a stronger focus on IWM has the potential to improve vegetable crop yield and quality, having beneficial side-effects for pest and disease management, and soil health (see Appendix 1, Section 5.14).

An extension officer in SA suggested that understanding the weed life cycle and the implications for control options was important. He suggested that options may be systemic, contact, or both, depending on the stage of weed life, In WA, a researcher considered the top research priority to be identifying 'whole of farm systems' best practices for weed management on farms where vegetables are produced. For several farmers and agronomists we spoke to, the main goal of IWM was to give farmers more effective options that did not require them to rely more heavily on herbicides. The benefits of this approach, according to a farmer in Tas, were to 'reduce their environmental impact, reduce the risk of herbicide resistance developing, and provide benefits to consumers'. Integrating non-herbicide weed management techniques is considered crucial to a sustainable industry future by several participants in our project (see also Sindel *et al.* 2011). IWM can simultaneously reduce farmer reliance on herbicides, and extend the useful life of the limited number of permitted herbicide options.

For a researcher in Qld, refining IWM within vegetable crops was the highest research priority for the industry, and had greater potential to improve farmer capacity to manage weeds than searching for new herbicide options. The researcher suggested that current weed management methods be reviewed individually, and weaknesses in each identified. Refinement and improvement of these methods could be undertaken to maximise their effectiveness, and novel options for integrating methods explored.

5.3.2. Decision support

Farmers and extension officers in NT and SA suggested that a decision support tool or 'matrix' may help farmers to decide on the most appropriate and timely weed control options, particular to their situation. Ideally, the tool might include the following details:

- *Weed ecology*: weed species present, seeding, life cycle.
- *Situation*: climate, soil type and condition, crop rotation, season, paddock history.
- *Weed management*: details on correct herbicide application, understanding of herbicide risk, best options for particular crops, control timing, and suitable and integrated non-herbicide control methods.
- *Economics*: return on investment, control costs.

A decision support tool of this nature could give the farmer the best options for weed management specific to their location (herbicide and non-herbicide), and may also provide a return on investment for different management scenarios. It could identify weeds specific to the area, provide a timeline for their management, and detail their impacts on specific crops. Farmers acknowledged that gathering the information required for a detailed decision support tool like this was an immense task, and that a more generalised tool may still be useful.

5.4. Management of specific weed species

Research is needed to explore in more detail the impacts on vegetable production of the most significant weeds found in crops, and management approaches targeting these species. Section 3.1 of this report suggests that this generally includes broadleaf weeds with a relatively short perenniality, such as fat hen, stinging nettle, mallow, pigweed, amaranthus, wild radish and blackberry nightshade, as well as the sedge nutgrass.

A greater understanding of the importance of these weeds in vegetable production is required. Issues of interest could include factors influencing germination and early growth, timing of emergence in field situations, optimising herbicide effectiveness, and methods for reducing seed set.

Several project participants suggested research activity for more effective management of particular weed species. Farmers and agronomists in Tas were concerned about limiting the spread of *Oxalis latifolia*, and were interested in methods to eradicate isolated outbreaks of this weed before it establishes. Since they believed that herbicides were ineffective against this species, alternatives considered included plastic mulch, steam treatment, solarization, and soil improvement.

Farmers and researchers in NT and Vic sought more effective methods for managing nutgrass and convolvulus (*Convulvulus* spp.). An organic farmer in SA was interested in more effective non-herbicide management of grasses such as kikuyu and ryegrass, while agronomists in SA sought to understand the link between stinging nettle infestation and soil health (specifically, potassium levels). Farmers in Qld sought integrated strategies for more effective control of common groundsel (*Senecio vulgaris*), and common thorn apple (*Datura stramonium*).

5.5. Weed management in specific crops

Some participants identified research projects required for specific vegetable crops, as well as specific environments. Generally, these suggestions came due to the lack of herbicide options within these crops, which means that weed management is more problematic (see also Section 5.1.1).

5.5.1. Brassicas

Farmers in Tas, Vic and NSW were interested in strategies to manage brassica weeds within brassica crops (Figure 5.5). Because selective post-emergent herbicides are not available for brassica crops (Section 5.1.1), other strategies are required. We observed many examples of excellent weed control within brassica crops in these states, in which a mixture of tillage, pre-emergent herbicides and hand weeding were used diligently and with appropriate timing to ensure maximum effectiveness. Farmers in WA suggested that the available pre-emergent herbicides allowed them to keep on top of weeds within their brassica crops. However, farmers still generally agreed that effective weed management in brassica crops was an ongoing problem. Nonetheless, the strategies adopted by successful farmers provide a good example for those struggling to manage weeds in general, and broadleaf weeds in particular, in brassicas. Several useful extension publications are available on pest and weed management within brassica crops (Appendix 1, Table 9.2).

Figure 5.5 Wild radish is an important weed of brassica crops, and is hard to manage due to its similarities to these crop species.

5.5.2. Leafy vegetables

Focus group participants in SA emphasised the need to improve weed control options in babyleaf rocket and spinach crops, given the growing market for these varieties. Because these are cut leaf crops, weed contamination is a major issue – a problem also noted by a cut leaf lettuce producer in Tas (see also Appendix 1, Section 3.3). Lack of post-emergent herbicide options means that other methods need to be used more effectively, or post-emergent options identified. Farmers in WA were interested in automated weeding technology and its potential for intra-row control in lettuce crops (see also Section 4.4.10), though further work in this area is needed.

5.5.3. Cucurbits

As has been discussed (Section 5.1.1), cucurbit farmers feel there is a lack of herbicide options for cucurbit production. Sindel *et al.* (2011) suggested that techniques such as stale and false seedbeds, early pre-plant irrigation, precision agriculture, using plastic mulch for more than one cucurbit crop, and farm hygiene need to be extended and adopted more widely amongst cucurbit producers. In this way, cucurbit production may remain feasible with a limited range of herbicide options. During this project, we observed a largely weed free organic cucurbit farm in NT, where a combination of tillage, plastic mulch and hand weeding were used effectively.

5.6. Weed management in specific regions of Australia

The fieldwork carried out during this project indicated that there are some vegetable producing districts in which circumstances suggest somewhat different weed impacts and the need for different approaches to management. Specific research, development and extension activity may be required to meet the particular needs of farmers in these regions.

5.6.1. The Top End

Vegetable production is expanding in Australia's Top End, with farmers producing vegetables in NT and the Ord River irrigation area in WA. Research on weed management specific to these non-traditional vegetable growing regions of Australia may be required. The Top End climate of hotter and more humid conditions and a long wet season results in different weed species of importance, and may require different best practices for weed management. As a result, some of the research on crop and weed management conducted in other parts of Australia may not be applicable to these farmers. These regions warrant specific research support from the industry, as their proximity to Asia could allow lucrative and expanding export markets to develop.

Some areas of research specific to the Top End are suggested here. These are covered in some more detail in other sections of this report:

- Management strategies for significant weeds within NT vegetable crops.
- Further development of biodegradable mulch films to suit the specific climate conditions of parts of NT (Section 5.2.1).
- Researching the role of weeds as virus, disease and insect 'refuges' during the non-production period of the northern wet season (Section 5.10).

A farmer in NT emphasised the need for HAL and/or researchers to work locally with farmers, agribusiness and government to ensure that research is locally relevant. He pointed out that NT is very different to other parts of Australia in the weed control challenges it faces, and so research needs to account for these conditions if the intention is to extend the research outputs to local farmers.

5.6.2. Peri-urban regions of Sydney and Melbourne

Vegetable farmers in peri-urban districts such as Richmond in NSW and Werribee South in Vic face significant economic and social challenges in managing their crops, and weeds within their crops, effectively. Our discussion with farmers in these districts suggested the following:

- Most farmers own relatively small blocks of land, and so must produce vegetable crops year-round in order to run a profitable, viable enterprise. This means that a range of promising or otherwise widely used weed control techniques are not available to these farmers, including extensive fallow herbicide rotation, green manure crops, biofumigation, solarization, and stale and false seedbeds. All such methods take time to complete, and do not fit into the busy schedule on these farms. At times, farmers are also forced by economic circumstances to keep growing the same higher value vegetable crop, rather than establishing a rotation of two or more vegetable crops. This can limit the post-emergent herbicide options available to the farmer.
- Land is very expensive in these urbanising areas, so that there is little or no prospect of business expansion within the district for farmers. This further restricts farmer capacity to build a fallow or non-vegetable rotation into their cropping cycle.
- Encroaching urban development limits some of the crop protection options available to farmers. For example, many farmers in these districts are unable or unwilling to use fumigants within their crops, because of the potential health risk to neighbours and their own families.

Weed management research in these districts may therefore need to focus on new herbicides, more effective crop rotations, intra-row tillage and precision agriculture, farm hygiene, weed seed bank management, and short-term stale seedbeds (where feasible, see also Section 5.2.10).

5.7. Environmental impact and soil health

Members of the vegetable industry are interested in the impact of the environment on their crop as well as the impact of their cropping activities on the environment, and wish to know more about strategies to benefit both crop and environment. Two farmers in Vic had observed that weeds were a much more significant issue in some seasons. They thought that environmental conditions played a major factor, including rainfall and temperature, but also soil health. A farmer in NT believed that a buildup of weeds was an indication of marginal climatic conditions and poor soil health. He had observed that weeds tended to survive longer than most other plants in poor conditions. He believed that increasing soil carbon would give his crops more chance of 'getting a head start on pioneer weeds'. Agronomists in SA believed that particular 'triggers' within the soil, such as high potassium levels, may lead to infestation with stinging nettle.

Several farmers and agronomists were concerned about herbicide residues in the soil, and the negative impact these may have on soil health and therefore crop yield. A farmer in Tas suggested that monitoring equipment was required to observe herbicide within the soil both within and after withholding periods. Agronomists in SA believed that cost-effective methods were required to decontaminate paddocks previously used for broadacre cropping, where herbicides tend to have longer residue than in vegetable production. The decontaminated land could then be turned to vegetable production. These agronomists felt that existing research activity on soil decontamination may be relevant.

Some farmers were interested in harnessing beneficial insects, diseases or viruses that may reduce the weed burden, by developing ecosystem corridors or refuge plantations (see also Section 5.2.12).

5.8. Economic impact

A thorough and detailed analysis of the economic impact of weeds on vegetable production is required, including the cost of managing weeds (Appendix 1, Section 3.1), and crop losses arising from weeds as a result from reduced yield and crop quality (Appendix 1, Sections 3.2 to 3.4). This research may involve fieldwork to determine yield declines in different vegetable crops arising from weeds, their impact on crop management, and analyses of the cost of control. Solid data on the economic impact of weeds will allow farmers to understand the true extent of their impact and why it is important to manage weeds effectively. It may also allow different weed management techniques to be compared on the basis of effectiveness and affordability.

It is important to bear in mind, however, that many of the methods used to manage weeds have other crop benefits and so are implemented for a range of reasons. Likewise, it can be difficult to determine the true reduction in yield caused by the presence of weeds within a crop. It can therefore be challenging to determine the actual economic impact of weeds on vegetable production.

Nonetheless, several farmers and agronomists were interested in economic impact data to demonstrate the actual cost of weeds, and to help determine the most cost-effective ways to reduce the weed burden. One way to begin to determine the economic impact of weeds, may be to focus on the cost of implementing particular control methods.

In order to determine the most economic 'mix' of weed control methods, a farmer in Vic was interested in cost-benefit analyses of various weed control and crop management methods, both short-term methods and long-term methods that may have a longer payback period. An extension officer in WA suggested that economic data was required to illustrate the true cost and benefit of using composted mulch in vegetables - and that the 'numbers needed to stack up' in order for this method to be viable. Economic analysis of biodegradable mulch application suggests that it is becoming more cost-effective compared to the alternatives (Section 4.3.2). Similar analysis may be feasible for other specific weed control methods.

Farmers in general are concerned about the cost of chipping and hand weeding (Section 4.2.1). Some farmers in NSW believed that up-skilling casual weeding staff would improve their efficiency and reduce the actual cost of weeding by hand.

5.9. Using existing research findings

This project has identified a number of overseas innovations in weed management in vegetable crops that may warrant introduction to Australia (Appendix 1, Section 6.4). In this chapter, we have provided examples of innovations in other sectors of agricultural production in Australia that may be relevant to vegetable cropping (see also Appendix 1, Chapter 8).

Farmers in WA pointed out that international work on weed management in vegetable crops is an important source for Australian researchers. One farmer stated that it was preferable to avoid 'reinventing the wheel' with research projects in Australia, where the work may have already been completed overseas. In such circumstances, it may just be a case of developing these research findings to better suit local conditions, and extending the results to farmers.

5.10. Linking weeds with other crop pests

Weeds are known to host a range of pests, viruses and diseases which impact negatively on vegetable crops (Appendix 1, Section 3.3, Table 3.2). Several agronomists, researchers and farmers interviewed for this project were interested in more research on the relationship between weeds and other crop pests. Weeds within crops and in surrounding non-cropping areas have the potential to act as 'refuges' for other crop pests (Figure 5.6).

A researcher in Qld wanted to see more research on the potential for pigweed to host disease, and the relationship of this and other weeds to viruses and diseases in tomato and potato crops. A researcher in Vic considered that weeds had a relationship to whitefly, nematodes, and two spotted mites.

In NT, focus group participants considered the top research priority in their district to determine which insect pests and viruses of vegetable crops were hosted by 'weeds in the bush' over the northern wet season (the non-cropping season in NT). In the Katherine district, vegetable farms are often surrounded by bushland in which a variety of weed species exist. These weeds were seen as an avenue for pests and viruses to carry over from one cropping season to the next. Participants believed that research was required to produce a list of host weeds for different insect pests and viruses. Previous work in the cotton industry to identify insect pests within weed refuges was considered a good starting point for this research. Management options for these weeds as refuges for pests and viruses includes using different production systems and crop rotations, and maintaining a high level of farm hygiene to minimise the risk of transference into the crop – for example, management of weeds along paddock boundaries.

Figure 5.6 Weedy non-cropping areas, such as this storage dam bank near Werribee, Vic, may be important refuges for crop pests, viruses and diseases.

6. Extension

6.1. Sources

There are a range of personal and media information outlets available to organisations such as HAL and AUSVEG in extending new crop protection techniques to vegetable farmers. These may include 'personal' sources of information, or 'media' sources of information.

Little information has been gathered previously on the information sources used by vegetable farmers, however research in the grazing industry suggests that the most highly rated form of personal or face to face information on weed management comes from expert sources; either weeds officers, spray contractors, or others recognised as experts in the region (such as experienced farmers). Field days and workshops were also very highly regarded (van der Meulen *et al.* 2006b; Sindel *et al.* 2013). Agricultural consultants such as private agronomists were considered somewhat useful information sources, although it is likely that graziers consult their agronomist far less frequently than vegetable farmers, given the different requirements of each production system. Preferred media information sources (Sindel *et al.* 2013) include weed best practice management guides, and government fact sheets and booklets.

In this project, we evaluated the range and usefulness of weed management extension material available to vegetable farmers. Sources of information used by Australian vegetable farmers are included in Table 6.1. 'Number of reported uses of source' refers to the number of occasions that a source of information was mentioned as being used during industry consultation for the project. This is only a guide on the most popular sources of information on weed control across the Australian vegetable industry, as a single mention at a focus group meeting has not been weighted differently to a single mention in a survey or during a farm visit. Number of reported uses is also not necessarily an indication of the trust placed in a source of information by Australian vegetable farmers as a group.

Table 6.1 Sources of information for the Australian vegetable industry, sorted by number of identifications during industry consultation (n = 65)

Source of information	Number of reported uses of source
Commercial suppliers and representatives	35
Workshops and field days	35
Other farmers/neighbours	30
Industry newsletters or magazines	29
Private agronomists and horticulturalists	26
Government agronomists and horticulturalists	19
Industry web sites	19
Email	16
Internet search	15
Booklets and fact sheets	13
Government extension professionals	12
Smartphone apps	7
Grower groups	6
Conferences and courses	5
Government web sites	4
Post	3
Newspapers	2
In person	2

Other useful sources mentioned during the project included universities, herbaria, and international study trips.

Research participants were asked which of the sources of information available to farmers on weed management was *trusted* the most. The response pattern was similar to that of the sources used (Table 6.1).

Table 6.2 Most trusted sources of information for the Australian vegetable industry, sorted by number of indications during industry consultation (multiple response)

Most trusted source of information	Number of indications
Commercial suppliers and representatives	10
Private agronomists and horticulturalists	10
Other farmers/neighbours	6
Government extension professionals	4
Grower groups	4
Email	3
Government agronomists and horticulturalists	3
Internet search	3
Self	3
Booklets and fact sheets	1
In person	1
Industry newsletters or magazines	1
Industry web sites	1
Post	1
Smartphone apps	1

6.1.1. Personal information sources

Personal information sources are the most commonly used by vegetable farmers, with commercial suppliers and representatives, workshops and field days, and other farmers also commonly used (Table 6.1). Furthermore, vegetable farmers appear more likely to trust these personal sources of information (Table 6.2). The research methodology used during this project (Section 2.2) also suggested that personal interaction is a more effective way to reach farmers than non-personal interaction such as a survey. Farmer and industry evaluation of some of the commonly used and most trusted personal information sources are included below.

Commercial suppliers and representatives

This category includes herbicide company representatives, and agronomists for companies such as Elders, Landmark, Serve-Ag or EE Muirs. Farmers are in regular touch with their commercial supplier representatives, who also often doubles as their agronomist, offering advice on crop protection and many other issues (see next sub-section). A farmer in SA pointed out that commercial suppliers may not have the answer to their question immediately, but in his case the supplier was part of a large national network, and so his contact is able to consult with colleagues elsewhere to answer his questions.

During this project we observed commercial supplier staff visiting farms in the absence of the farmer, making recommendations to farmers, and then ordering products on their behalf. Farmers have a close working relationship with the supplier, and often trust their advice implicitly. As a farmer in NSW commented, 'we have to trust the reseller, because we don't feel we have the background knowledge to understand the science behind the chemical options'.

A commercial agronomist in Tas commented that there was almost an oversupply of commercial suppliers and advisory staff in that state, with farmers having daily access to their advisor if needed. In contrast, farmers in WA noted that there are few agronomists attached to commercial supplier companies at their disposal, so that they must rely more heavily on other sources of information, or their own experience and judgement.

Farmers who worked regularly with a favoured supplier were generally very satisfied with the advice they received. Where farmers had misgivings about commercial supplier advice, it was often to do with a perception that their advice was not truly independent, and that their underlying agenda was to point farmers towards product purchases in their own range. A farmer in NT did not trust the independence of local supplier advice, and preferred to consult with government or extension staff instead. Another farmer in SA stated that the advice received from his supplier varied in its relevance and effectiveness.

Private agronomists and horticulturalists

Many commercial suppliers servicing the vegetable industry have an attached agronomist and/or horticulturalist, and so for many farmers, their 'commercial supplier representative' was also their agronomist/horticulturalist. In some cases, farmers consulted with an independent agronomist or horticulturalist, though many worked for a commercial organisation (see previous sub-section).

Farmers who considered their agronomist or horticulturalist to be their most trusted source of information valued their capacity to 'filter' new information, products and techniques, and advise the farmer on which of these was applicable to their farm. Farmers often lack the time to research new approaches to crop management, and feel overloaded by the vast amount of information at their potential disposal. Agronomists have access to a large number of farmer clients, and represent a trusted, highly informed and efficient information network through which to reach farmers. A farmer in NT considered his agronomist to be 'a critical lifeline', while another in Vic commented:

> *I won't believe that something is worth trying until my agronomist tells me it is. I know he will have researched the approach and seen it in action to know that it is worth doing.*

Other farmers and grower groups

Farmers will consult with their neighbours, or other farmers in the district, on weed management issues where they know they have some common ground – for example, crop or weed type. Several strong grower groups exist in vegetable growing regions around Australia (Appendix 1, Section 9.3.2). In some districts, farmers are working towards a group approach. Several farmers rated grower groups as their most trusted source of information.

Occasionally farmers will consult others from outside their district, for example fellow organic farmers, or colleagues they met at an industry field day or conference. A farmer in WA commented that other farmers are helpful to 'bounce ideas off'.

However, vegetable farmers do not always trust the advice given by their neighbours. A number of farmers and agronomists throughout Australia commented that farmers can be very secretive, and at times unwilling to help their neighbours gain a commercial advantage by offering them free advice. An extension officer stated that it could be difficult to get vegetable farmers together to share advice and learn from each other, perhaps because they are so busy year round. However, the extension officer observed that when farmers to get together, they always enjoy the experience and learn a lot from each other.

Workshops and field days

In order for farmers to attend and benefit from a workshop or field day:

- the topic needs to be relevant to their production system; and
- the event needs to be timed to fit in with their hectic schedule.

Often, farmers also prefer such an event to include a product demonstration, for example at a research farm.

Some areas appear to be serviced quite well by workshops. One example is the Richmond district in NSW which is located near a large government research facility. In this district, farmers and agronomists were strongly supportive of demonstration farms, and were concerned that these may be less common in the future. Farmers and extension professionals alike commented that workshops and field days require an on-ground coordinator to be effective, such as a regional extension officer or an industry development officer. Farmers in the Lockyer Valley in Qld felt that a regional development officer was required to facilitate beneficial local workshops.

Government agronomists and extension professionals

Many vegetable farmers value personal government information sources highly, viewing them as an 'independent' (and free) alternative to the commercial or private agronomist. Currently available services are summarised in Appendix 1, Section 9.3.1.

However, farmers advised us that recent government funding reductions across Australia has resulted in many government agronomists and extension staff losing their positions, with the remaining staff being too busy to consult with farmers regularly. Some districts no longer have a government agronomist, horticulturalist or extension officer. Reduction in government staff numbers also means that highly beneficial workshops and field days are becoming less common.

Focus group attendees in Tas commented that a short-term funded industry development officer was present in the state until recently, and that this person were a very useful source of advice. HAL-funded extension staff are currently working in NT and WA, and are highly valued by farmers. Farmers in the Lockyer Valley in Qld are seeking to co-fund their own regional industry development officer. There is an opportunity for HAL and AUSVEG to help fill the gap left by declining government extension services by funding or co-funding extension officers or industry development officers in other states and regions.

6.1.2. Written information sources

Examples of published resources are listed in Appendix 1, Section 9.3.3, Table 9.2. The most commonly used written information source amongst vegetable farmers appears to be industry newsletters and magazines (Table 6.1). The AUSVEG magazine is commonly read by farmers, and the headlines in such magazines helped farmers decide whether or not an article was relevant, so that getting the headlines right to draw farmers into a useful article was considered vital. NSW focus group participants felt it was important to keep the written information simple in these stories. By this, they meant writing stories in a clear, non-academic style, accessible and understandable to farmers, and providing contact details for further information.

A range of information guides and fact sheets are available on weed management in vegetables. Some of these deal explicitly with weeds, while others address weed management as an aspect of crop protection (for example, to eliminate or minimise host plants for viruses, pests and diseases; Appendix 1, Section 9.3.3). Table 6.1 suggests that booklets and fact sheets are somewhat commonly used amongst vegetable farmers as a written information source, although there was little indication that this source was amongst the most trusted (Table 6.2).

Some farmers mentioned factsheet publications such as the 'VegeNotes' published by AUSVEG as useful sources of advice in a concise format. The 'Weed Deck' identification resource was considered important, and designed for use in the field (for example being stored in the vehicle glovebox). A researcher in SA suggested that factsheets needed to be easily accessible, and succeed in getting discussion on important topics started amongst farmers.

6.1.3. Online information sources

Examples of web-based information about vegetable crop management provided by government departments are listed in Appendix 1, Section 9.3.3, Table 9.3. Online sources include downloadable factsheets, industry websites, email, and smartphone applications.

Commonly used online information sources on weed management include industry websites, email, internet search, and smartphone applications (Table 6.1). Of these, email was most likely to be rated 'most trusted' (Table 6.2).

Farmers mentioned receiving emails such as the AUSVEG updates, government emails to industry such as 'AgMemos' in WA, and commonly being in touch with their agronomist via email. A farmer in NSW suggested that emails should be sent to their agronomist first, who can filter the information for the farmer, and forward it on if it is relevant (see also Section 6.1.1). Some farmers are technology savvy, and carry a smartphone with them on which they access emails during the day. These farmers rated email as highly important, however other farmers prefer written or face to face forms of communication, and are better reached through their agronomist.

Websites commonly consulted by farmers and agronomists include AUSVEG, FarmOz, AgWorld, PestGenie, InfoPest, government websites, and the APVMA (for herbicide labels, minor use permit and registration details). Some farmers were positive about the APVMA website, while others found it very difficult to use for accessing relevant information. These websites are convenient and important resources for farmers, when they have time to carry out their own research, or need to find out information (such as herbicide label details) quickly. Where farmers need to find out about a more specific crop issue, many will search the internet, and form their own opinion on the best approach to take in their own crop. Internet searching is a relatively common source of information for farmers (Table 6.1).

Agronomists appear to rely heavily on email, and are also in regular contact with their farmers via phone and text message. Many farmers commented that they would be happy to receive more information on aspects of weed management via email, although some preferred that it was sent to their agronomist first, who could evaluate the relevance of the information to the farmer.

Several farmers suggested that an online decision support tool would be a very helpful resource for them to make crop and weed management decisions (Section 5.3.2), and may be delivered online.

Smartphone applications ('apps') are only used by a relatively small proportion of vegetable farmers at this stage, but appear to have potential in the near future to extend information to farmers quickly and conveniently. Apps used by farmers include the APVMA chemical registration app, the AUSVEG app, 'Livefarmer', and apps for tank mix calculation, weed identification and pest management. A farmer in Vic suggested that making more information available through apps would be useful to him. Apps used in related industries such as broadacre cropping may also be relevant to vegetable farmers.

6.2. Information needs

6.2.1. Weed species

Vegetable farmers need to understand the impact of particular weeds on their crop, in order to be motivated to implement targeted control strategies (Section 5.4; see also Appendix 1, Section 7.2). Weeds mentioned by farmers consulted during the project for which they would like more information included chickweed (Vic) and oxalis and cleavers (Tas).

Several published and online weed identification, behaviour and control resources are available (Appendix 1, Section 9.3.3), and are used by some farmers and agronomists. However, the review of extension literature in this report did not identify any impact and management publications addressing particular weed species within vegetable crops. A researcher in Vic, as well as a farmer in WA, suggested that farmers needed weed identification resources which include information on weed life cycles, and appropriate timing for control activity. An agronomist in Qld was regularly consulted by his clients on weed identification and management, and believed farmers would benefit by also having this information at their fingertips.

A number of books exist that are useful for weed identification (for example Wilding *et al.* 1986, Auld and Medd 1992). Some of these resources include clear photos of weed seedlings, at the stage when they need to be controlled.

6.2.2. Weed impact

Vegetable farmers need to have more information on the impact of weeds on their bottom line (yield and quality of the crop, and impact on farm management). The results of the economic impact research recommended in Section 5.8 should therefore be extended to farmers, perhaps in the form of case studies. Such information will help farmers with decision making in relation to weed management.

6.2.3. Chemical control

Registration and minor use permits

Farmers in Tas and Qld were interested in receiving further information on new herbicides available for vegetable production, and alerts on when new herbicides become available.

A farmer in Tas previously had a personal contact on herbicide information and permit details, but has lost this resource recently and requires this information to be readily available. A HAL contact considered that farmers need to be made aware of which herbicide groups are at risk of being removed from the permitted list, and why.

In WA and NSW, farmers were interested in keeping up to date on herbicide permit renewal dates, details of minor use, and permit expiry notifications. Several project participants expressed an opinion that HAL needed to do more to support farmers and agronomists to facilitate off-label use of herbicides through minor use permits.

However, we have been advised that support is readily available for trials and minor use permit registration from HAL (although proposed changes to the cost recovery model for minor use permit trial and registration activity may threaten this process; Woods 2014). Minor use permit application requests are submitted to AUSVEG, and then HAL works with the applicants to gather the data required for obtaining the permit successfully. Many farmers and even agronomists did not appear to be aware that this service exists. Some may also consider that they are too busy to spend the time working with HAL, AUSVEG and/or the APVMA to obtain a minor use permit.

More efficient herbicide use

Researchers and farmers in Vic, Tas and WA suggested that farmers needed continual training and information on the latest herbicide application techniques and technologies. Factors include adjusting spray equipment and nozzles to minimise drift and ensure maximum coverage (where technology already exists in broadacre cropping according to NT focus group participants), appropriately matching equipment against herbicide type, water quality, herbicide resistance and rotations, understanding mode of action, correct rates, appropriate timing of application, climate conditions, tank mixes, understanding herbicide risks, labelling, record keeping, disposing of containers, and cost effectiveness.

In SA, a researcher suggested that farmers need more information on herbicide effectiveness within some of the main vegetable crops, including carrots, brassicas, lettuce and potatoes. The researcher suggested that farmers need to know which major weeds are controlled by herbicides within each individual crop, and also which weeds can be managed by incorporating crop rotations and herbicide use – for example, rotating brassica and lettuce crops to control a broader weed spectrum.

A HAL staff member emphasised the usefulness of demonstrating herbicide use efficiency to farmers *in person*, for example in the farmer's paddock or on a demonstration farm. NSW focus group attendees confirmed that demonstration farms were vital in both developing and distributing this information. The HAL staff member emphasised further that it should not be taken for granted that farmers have the time to fully understand herbicide labels.

Focus group attendees in NSW suggested that most of this information is already accessible to farmers, but that farmers do not necessarily receive the information, or may not be willing to try new techniques to use herbicides more effectively. They suggested that farmers are often happy to keep using a strategy when they know it is working well, even if the approach may not be sustainable.

Herbicide resistance

According to a number of farmers, researchers and agronomists, farmers may require more information on herbicide rotation options available to them and which herbicides manage particular weeds the most efficiently, to help minimise the risk of herbicide resistance developing. Emphasising to farmers the need to use correct rates was also considered important in addressing resistance. Finally, the importance of controlling survivor weeds using non-herbicide methods or herbicide rotations needs to be highlighted.

Environmental impacts

In Vic, a researcher considered that farmers need more information on the off-target impact of herbicides, including water contamination, persistence, drift, and health hazards. An agronomist in Qld suggested that more information was required on crop plant-back periods for pre-emergent herbicides. A farmer in SA was interested in receiving more information on herbicide and fungicide safety.

Agronomists in SA believed that some farmers were not aware how to use metham sodium fumigant correctly, and that correct fumigation techniques should be shown at demonstration sites.

6.2.4. Current and innovative weed control methods

Extension of innovative weed control approaches, or ones with a relatively low uptake amongst vegetable farmers (Sindel *et al.* 2011) is recommended. Some of these require more research to validate their effectiveness; others are already known to benefit farmers, while there appears to be misinformation within the industry about others. If their usefulness can be clearly demonstrated (Section 5.2), methods worthy of wider extension to farmers may include biofumigation and green manure crops, mechanical weeding and precision agriculture, stale and false seedbeds, biodegradable mulch, and farm hygiene.

Biodegradable mulch

Farmers in Tas and Qld expressed an interest in more information on biodegradable mulch options, although the farmer in Qld stated they had a 'bad experience' with biodegradable mulch. A researcher in Qld highlighted one aspect of the misinformation that seems to be present in the industry about biodegradable mulches. The researcher pointed out that some polyethylene products were marketed as 'biodegradable' products, when in fact they only break down into smaller pieces, and not completely such as true, starch-based biodegradable mulches.

Mechanical weeding

A researcher in Tas suggested that mechanical weeding technology, incorporating GPS, has the potential to advance to the extent that herbicide use may not be necessary in the future. He believed that any relevant research in this area needed to be extended to farmers so that they are 'kept up to speed'. Demonstrations were also suggested where technology appeared to be beneficial, either on demonstration farms or by vendors. A farmer in Vic, and focus group participants in NT, showed an interest in more information on innovative weeding implements such as mechanical intra-row technology.

Green manures and biofumigation

A researcher in Vic suggested that a demonstration of the benefits of green manure crops and biofumigation (Sections 5.2.3 and 5.2.4) was required. In an intensively cropped area such as Werribee South, Vic, farmers do not feel they have the time to institute a green manure or biofumigant crop (Sections 4.4.3 and 4.4.4). However, the researcher suggested that a demonstration farm in the district was the best way to illustrate the benefits of green manure crops.

Hand weeding

While improvements may be possible to hand weeding implements (Section 5.2.5), farmers may also need to be updated where relevant on new hand weeding tools and techniques, to increase hand weeding speed and therefore reduce labour costs.

6.2.5. Integrated weed management

Relatively little extension information is available on IWM in vegetable crops. The recently commissioned HAL project VG13078 'Extension of Integrated Crop Protection information' is expected address this information gap, as IWM is an important aspect of broader ICP/ICM (see also Appendix 1, Section 5.14). IWM was considered important by an agronomist in Qld, with farmers 'running out of chemical options, especially with resistance developing'. An agronomist in Tas also emphasised the importance of integrated approaches to address herbicide resistance. Farmers indicated they were interested in IWM of particularly troublesome weeds. A researcher in Qld suggested maximising the effectiveness of individual and integrated weed control methods (Section 5.3.1), and believed that a demonstration farm was one way to show farmers what could be achieved by combining methods effectively. There is an opportunity to extend IWM more effectively to vegetable farmers, the vegetable industry potentially using the high quality IWM research and extension work of the Australian grains and cotton industries (Appendix 1, Sections 8.5 and 8.6).

6.2.6. Region-specific information

A few farmers and other project participants commented that information needs to be relevant to their particular needs in order to be useful. For example, those in Tas and NT commented that information on weed control needed to take into account the unique conditions faced by farmers in each of these regions.

In SA, focus group attendees felt that not enough information was provided to non-English speaking farmers in vegetable growing districts such as Virginia, and that this meant some practices adopted by those farmers were inappropriate, such as herbicide use. Similar problems were noted to varying degrees in WA, NSW and NT, though in some areas such as WA and NT, HAL-funded extension staff have been able to address this issue with some success. Several people did note, however, that farmers from particular ethnic communities were less likely to attend face to face extension activities, so alternative approaches may be needed.

Recommended awareness raising amongst ethnically diverse farmers may include publishing articles in ethnic newspapers, employing ethnic extension officers, or motivating the children of ethnic vegetable farmers to study agronomy and take an agronomic role advising farmers in their local district.

7. Research, Development and Extension Plan

7.1. Approach

In this chapter, we present research, development and extension (R, D & E) priorities emerging from this national scoping study. These were identified by the researchers through discussion with industry stakeholders, a review of relevant literature and analysis of the report results.

Research and development issues have been presented separately to extension issues in the next two subsections, although there is often overlap between the two. Introducing a newly developed technique or technology will require effective extension to maximise adoption amongst farmers.

Issues have been grouped into a number of 'themes' of research and development or extension, addressing weed management and impact. These themes have been presented in priority order. Within each theme, at least one R, D & E issue is presented, with some themes including several issues. Many of these issues will have broader relevance than weed control, and may improve the capacity of farmers to manage their vegetable crops in a number of ways, including pest and disease management. The following columns are included within the tables of issues.

- *Issue*: the priority issue to be addressed.
- *Report Section*: reference to relevant sections within the report for background information.
- *Importance to Industry*: to what extent the issue is desirable to farmers and other industry stakeholders. This has been determined on several criteria, including the number of times the issue was discussed during industry consultation, the ranking of importance given to the issue (for example, during focus group meetings where attendees were asked to rank R, D & E issues), and the subjective determination of the researchers.
- *Feasibility*: how practical it is to carry out the research, development or extension activity, and how likely it is to be adopted. This has been determined on the basis of the literature review, industry consultation, and the research team's experience with these issues. A particular research topic may be very important to the industry because of the potential benefits it can reap, though feasibility may be low if there is little prospect of implementation or adoption.
- *Rank*: determined through the combination of 'Importance to Industry' and 'Feasibility', so that an issue with high industry importance and low feasibility may be ranked 'medium'. These determinations were made by the research team and are open to interpretation, though will be helpful in determining where industry funds should be spent on weed control R, D & E.

In the next two sections, general recommendations are made pertaining to the research and development plan, and the extension plan respectively. Specific comments on each theme are followed by tables containing the research and development plan, and the extension plan (Tables 7.1 and 7.2).

7.2. Research and Development Plan

7.2.1. Introduction

Any research and development activity on weed control in the Australian vegetable industry should commence with a detailed exploration of relevant R & D work that has been carried out in broadacre cropping in Australia, as well as relevant work that has been carried out in both vegetable and broadacre production outside Australia.

It may be possible to adapt techniques used in other industries, or overseas, to Australian vegetable production with relatively little research or development required. For example, new herbicide options may be available amongst those already registered for other crops in Australia, or amongst the range of herbicides used in vegetables outside Australia.

Herbicides appear to be the most important single form of weed management for conventional vegetable farmers, and therefore new herbicide research has been included in this research and development plan as the top industry priority for improving weed control.

Despite this, it is crucial to continue research into making existing non-herbicide control methods more efficient and affordable, and to foster innovative methods where these become available. Sustainable vegetable production in Australia will rely on a suite of weed control methods, integrated together into an effective and affordable strategy. Relevant research that has been carried out in organic vegetable production systems can also provide potentially useful information in this regard.

7.2.2. Research and Development Priorities

Priority Level 1

New Herbicide Options

New herbicide options are the top research and development priority within the vegetable industry. This area was identified by all conventional farmers, agronomists, extension staff, as well as most researchers consulted, as a crucial ongoing research and development activity.

The feasibility of introducing new herbicides is influenced by the availability of products (including new chemistry), their potential effectiveness, the relatively small and fragmented Australian market, and the feasibility of using herbicides for certain crops. The cost of trial and registration work is also a significant stumbling block, and suggestions to improve this process include greater recognition of international trial data, industry support of trial activity, better communication of avenues to apply for minor use permits, and more effective use of the minor use permits scheme (Section 5.1).

Biodegradable Mulches

Biodegradable mulches have become more affordable and cost-effective in the past decade. Continued improvements and falling costs as production is scaled up, means that they are poised to offer a realistic alternative to conventional plastic mulch, and an alternative option to herbicides in crops not traditionally grown with plastic mulch. We therefore consider their ongoing development to be a high industry priority to sustain effective weed control in some crops.

Research priorities include trials in different regions of Australia to expand their useful range. More understanding is required on associated littering issues (what are the littering issues and which products do these relate to) and whether biodegradable trickle tape is feasible to use alongside biodegradable mulch.

Biodegradable mulch options may include 'spray-based paper mulch', of the type used on roadside verges, and discussed in Section 5.2.2.

Management of Specific Weeds

Many farmers and other industry participants were interested in specific management options, or in some cases localised eradication, for particular weed species of importance in their region. Examples include major weeds such as fat hen, wild radish and nutgrass, but also weeds of growing importance in some parts of Australia, such as *Oxalis latifolia* in Tas (see Chapter 3). Comprehensive studies are recommended on the improved control of these important species.

Priority Level 2

Herbicide Resistance

Herbicide resistance is already apparently evident on some vegetable farms and in other industries, and has considerable potential to develop in the next decade given the heavy reliance of most farmers on a limited range of herbicides. A greater understanding of weed resistance to these herbicides may involve resistance testing on vegetable farms. This work can also draw heavily on work in broadacre cropping in Australia, particularly where the herbicide products, weed species and regions are relevant to vegetable production. Extension of herbicide resistance data and risk mitigation strategies is important, to give farmers the opportunity to extend the useful life of their limited herbicide options.

Weed Seed Bank Management

Several farmers and agronomists highlighted the importance of reducing the weed seed bank in the soil within their paddocks as the key to longer-term weed control within their crops. The foundation to weed seed bank management appears to be *effective crop bed preparation*, including a range of techniques such as pre-plant herbicides, tillage, stale or false seedbeds, green manure and biofumigation crops, and in some cases soil solarization or fumigation. Once the crop has established, seed bank management involves controlling inter-row and intra-row weeds before they set seed, for example through precision tillage, hand weeding and selective herbicide application where available.

However, the effectiveness of the main weed control methods in reducing the weed seed bank is poorly understood. Identifying and extending these methods will improve the capacity of farmers to manage the weed seed bank.

Development of Other Weed Control Methods

Research and development work is required to improve the effectiveness of a range of non-herbicide weed control techniques.

As a part of an annual crop rotation, green manure and biofumigant crops have shown considerable potential to control weeds in some locations (such as the biofumigant crop 'Caliente' in Tas), but have been less effective elsewhere. More research and development in green manure crops may focus on the selectivity of biofumigants for important weed species, the mechanisms through which they achieve weed control, and optimal use including best practice incorporation techniques. Testing in different locations across Australia will also demonstrate their relative effectiveness.

Improvements in managing inter-row weeds may include: utilising drip irrigation within the crop rows in a greater variety of crops to leave the inter-row space relatively free of soil moisture; and adjusting planting orientations to the east-west axis to shade wheel tracks and inter-row weeds while maximising light interception and therefore productivity of the crop.

Hand weeding is a must for most vegetable farmers, and is one of their most significant production costs. Improving hand weeding technology and techniques may reduce the economic burden of weed control for many farmers.

Priority Level 3

Economic Impact of Weeds

Developing reliable data on the costs and benefits of weed control at the farm level will allow farmers, researchers and policy makers to understand the true extent of their impact and why it is important to manage weeds effectively.

A focus of this research may therefore be on cost-benefit analysis of particular weed control methods, to allow their relative affordability and effectiveness to be understood by farmers. Examples identified during industry consultation included: green manure and biofumigant crops; crop rotation; soil solarization; and a comparative study of intra-row tillage with selective post-emergence herbicides and/or hand weeding.

Precision Agriculture

Considerable work has been carried out in other industries, and overseas, on precision agriculture technologies designed to improve weed control options available to farmers. Related technologies include plant sensors, variable rate and targeted herbicide application technology, precision intra-row tillage and slashing, GPS, and weed mapping.

Researchers in Australia have undertaken research into weed control robotics. This and other precision technologies have potential relevance to vegetable farmers in the longer term as they become more effective and affordable for the generally smaller scale Australian vegetable farm, and so ongoing research in this area is warranted.

Reducing Tillage

Reduced or no-till has become popular in broadacre cropping. In vegetable production, this approach may be associated with using living and killed cover crop mulches, soil solarization, and thermal weeding methods. Reduced tillage was rare amongst the farmers consulted for this project. However, solarization under plastic mulch, or during summer fallow periods in hot and/or wet climates such as in south-west WA and NT, was used effectively by some farmers to reduce the weed burden. Other farmers were experimenting with killed cover crop mulches. The benefits of these approaches to vegetable farmers, as well as others that foster a reduced till approach to weed control, require further research.

Table 7.1 Research and Development Themes

Priority Level 1

R&D Issue	Report Section	Importance to Industry	Feasibility	Rank
New Herbicide Options				
Carry out a feasibility study for registering the pre-emergent herbicide prosulfocarb/s-metolachlor for use in onion and carrot crops.	5.1.2	High	Medium	***High***
Explore the feasibility and/or necessity of permanently registering the herbicide phenmedipham, rather than rely on ongoing renewal of minor use permits.	4.1.4	High	Medium-High	***High***
Carry out a feasibility study for registering the herbicide clopyralid for use in brassica crops.	5.1.1	High	Low-Medium	***Medium***
What is the current status of the Australian phenmedipham/flumetsulam mix trials for post-emergent broadleaf weed control in lettuce? Can the findings be extended to farmers? Is more work warranted?	5.1.1	High	Medium	***Medium***
Carry out a feasibility study for registration or minor use permit for using dimethenamid-p to control nutgrass in onions.	5.1.1	High	Low-Medium	***Medium***
Carry out a feasibility study for new post-emergence herbicide options to control broadleaf weeds in lettuce.	5.1.1	High	Low	***Medium***
Identify herbicide options for minor vegetable crops.	5.1.1	High	Low	***Medium***
Biodegradable Mulches				
Continue research and development activity to improve the effectiveness and affordability of biodegradable mulch options, and extend this plus current best practice use to farmers and their agronomists.	4.3.2; 5.2.2; 6.2.5	High	Medium-High	***High***
Management of Specific Weeds				
Determine the feasibility of improved management or localised eradication of	5.4	High	Medium	***High***

important weeds on vegetable farms.

Priority Level 2

R&D Issue	Report Section	Importance to Industry	Feasibility	Rank
Herbicide Resistance				
What is the extent of weed resistance to the major herbicides used in Australian vegetable production?	5.1.5	High	High	***High***
Weed Seed Bank Management				
Identify and extend the effectiveness of the main weed control methods in reducing the weed seed bank.	5.2.11	Medium-High	Medium	***Medium***
Development of Other Weed Control Methods				
What is the effectiveness of green manure crops (including biofumigant varieties) on weed suppression and weed seed bank reduction?	4.4.4; 5.2.4	Medium-High	Medium-High	***High***
What is the impact on weed germination of using drip irrigation and/or east-west crop row orientation to reduce light and moisture between rows?	4.4.6; 4.4.12; 5.2.14	Medium	Medium-High	***Medium***
What are the benefits and general principles of crop rotation for weed control?	4.4.5; 5.2.6	Medium-High	Medium	***Medium***
Identify improvements to hand weeding implements and techniques, and develop materials to extend best practice hand weeding techniques to farmers and their staff.	5.2.5; 6.2.4	Low	Medium-High	***Medium***
What is the feasibility of establishing cover plantings in non-cropping areas, to reduce weed refuge spaces alongside and within vegetable paddocks?	5.2.3	Medium	Low-Medium	***Low***
What is the role of weeds as refuges for beneficial organisms, and crop pests and diseases? How can the benefits and risks be optimised?	5.2.15	Medium	Low	***Low***
Carry out more research into the effectiveness and affordability of thermal weed control methods for Australian vegetable crops.	4.4.2	Low	Medium	***Low***

R&D Issue	Report Section	Importance to Industry	Feasibility	Rank
Development of Other Weed Control Methods *(continued)*				
Evaluate the feasibility and desirability (including community acceptance) of genetically modified 'herbicide resistant' vegetable varieties.	5.2.13	Low	Low	***Low***
Is livestock grazing an effective and feasible weed management strategy during crop fallow periods?	5.2.15	Low	Low	***Low***
Priority Level 3				
Economic Impact of Weeds				
What is the economic impact of weeds in vegetable crops at the farm level, including the cost of specific management methods, and the impact of weeds on final marketable yield?	5.8	Medium	Medium	***Medium***
Precision Agriculture				
Refine and improve precision agriculture, weed detection and targeted herbicide application technology, with special reference to relevant work in other industries. Seek to make the technology effective and affordable for smaller scale vegetable farming.	5.2.7; 5.2.15	Medium-High	Medium	***Medium***
Continue work on robotic weeding technology for vegetable crops.	5.2.7	Medium-High	Medium	***Medium***
Can GPS technology be used with digital elevation models to improve the effectiveness of GPS in undulating landscapes?	4.4.9	Low	Low	***Low***
Reducing Tillage				
What are the benefits of soil solarization for weed control?	5.2.9	Low-Medium	Low-Medium	***Low***
What is the feasibility and benefit of using living and killed cover crop mulches as an alternative to plastic mulch?	4.4.3; 5.2.3	Low-Medium	Low-Medium	***Low***

7.3. Extension Plan

7.3.1. Introduction

Some broad recommendations are made for *face to face* and *written* extension, based on our discussion with farmers and others involved in the Australian vegetable industry.

- *Agronomists* (particularly private agronomists) are the most important and trusted source of information for the large majority of vegetable farmers, and farmers generally have a close working relationship with their agronomist. Agronomists are therefore the ideal avenue through which to extend weed control innovation to farmers.
- *On-farm demonstrations and field days* are highly valued by farmers seeking to understand more about an innovative technique or technology. This approach allows the farmer to see the innovation in action, and to discuss its potential benefits with those actually using it in the demonstration. Demonstration sites may be established on a government research farm, though a more affordable alternative may be regionally-based trials on private farms, in a location accessible to other farmers interested in the trial activity.
- Effective field days must feature topics in which farmers are likely to be interested. A 'local champion', such as an extension officer or locally respected agronomist, is required to organise events most effectively.
- It is important to work with farmers at the local level for both research and development, and extension activities. Adoption rates will be higher if farmers can appreciate the *local relevance* of the innovation.
- News items (magazines, email newsletters and web sites) must be written in a non-academic style, with a clear and easy to understand headline that captures the farmer's attention immediately if the innovation is relevant to them.

Multiple forms of extension are vital to reach the highest possible proportion of farmers, using a mixture of online, written and face to face sources and delivery avenues. Given that there is a large number of farmers of non-English speaking backgrounds in the Australian vegetable industry, information should also be provided in multiple languages where relevant.

7.3.2. Extension Priorities

Region-Specific Extension

HAL currently funds industry development/extension staff in WA and NT. These staff provide an important service to farmers, extending innovations in crop management as well as organising meetings at which farmers benefit from interaction with experts and their peers. Face to face extension is generally considered the most effective way of reaching farmers (Appendix 1, Section 9.2). HAL support (funding or co-funding) for industry development positions in other key vegetable growing regions across Australia will therefore benefit the industry generally. Potentially, additional industry development positions might be supported in Bowen, Bundaberg and the Lockyer Valley in Qld, as well as Sydney, Melbourne, Tas, and Adelaide.

The development of extension materials and the provision of extension services has been changing over time from a predominantly public model to the current approach which has a blend of public and private extension providers. It is anticipated that the move away from public sector extension will continue and this may have implications for how weed management information is compiled and communicated in future.

Promoting efficient herbicide use

Efficient and sustainable use of chemical options for weed control can extend the useful life of the limited range of herbicides available to farmers, and reduce the risk of adverse environmental or health impacts. Development of resources in the area of efficient and effective herbicide use might involve consultation with the industry, as well as a review of efficient practices conducted in other agricultural sectors, or overseas. In some regions, extension needs to reach non-English or English as a second language farmers in addition to English speaking farmers.

Minor use herbicide permits

In this project, we found that the herbicide minor use permits program is a relatively straightforward way for farmers to broaden the range of herbicides available to them in vegetable crops. However, few farmers were aware that this service existed through HAL and the APVMA.

In addition to more effective and regular extension of the benefits and processes of the minor use program, we recommend that the program itself be revisited. Streamlining the process would make it easier for farmers to access more chemical options, though we acknowledge this may not necessarily be a desirable goal, economically or environmentally. Proposed changes to the minor use program (Woods 2014) may restrict the capacity of the industry to apply for minor use permits for chemicals in the future. However, the program's continuation appears to be very important to the ongoing capacity to control weeds in vegetable crops.

Promoting Integrated Weed Management

Currently available written extension materials on weed management in vegetable production generally address specific crops or regions (Appendix 1, Section 9.3.3). However, an Integrated Weed Management (IWM) manual, similar to that available to grains and cotton farmers in Australia would be an important resource for vegetable farmers struggling to control their weeds. Such a manual may be provided in hard copy, or made available online or as a smartphone app.

Topics may include: information on the economic benefits of weed control; herbicide resistance occurrence and management; general IWM techniques; IWM specific to major vegetable crops; identification, ecology and management of the most important weeds of vegetable production (including management at different stages of the weed life cycle); and case studies of successful IWM strategies in different regions.

IWM is the key to an effective weed control strategy in the medium-long term, and on vegetable farms the mix of techniques used will vary. It will be important as part of IWM extension activity to emphasise the importance of sustainable herbicide use to farmers. This may include improved herbicide use efficiency, herbicide rotations, and awareness that currently available herbicides will eventually lose their effectiveness unless survivors are eliminated before setting seed. Improving efficiency, and greater reliance on non-herbicide methods, is therefore vital to sustainable vegetable crop production.

Decision Support Tools

Integrated decision support tools for crop protection strategies (including weed control) would help farmers decide on the most appropriate and timely weed control options. The tool may be provided online, as a computer program or as a smartphone app. Such a tool would require complex data, so a feasibility study only is recommended at this stage.

Table 7.2 Extension Themes

Extension Issue	Report Section	Importance to Industry	Feasibility	Rank
Region-Specific Extension				
Industry development/extension officers (culturally specific where relevant) funded or co-funded by HAL for all major vegetable growing regions of Australia.	6.1.1	High	High	***High***
Promoting Efficient Herbicide Use				
Extension publication and/or demonstration: correct choice of spray equipment for herbicide application - including innovative technology and techniques, and appropriate use of tank mixes.	4.1; 5.1.6; 6.2.3	Medium	High	***High***
Extension program: 'Always Follow the Label' - correct use to ensure herbicide sustainability.	5.1.6; 6.2.3	Medium	High	***High***

Extension Issue	Report Section	Importance to Industry	Feasibility	Rank
Promoting Efficient Herbicide Use *(continued)*				
Extension publication and/or demonstration: safe and appropriate use of fumigation in vegetable farming.	6.2.4	Medium	Medium	***Medium***
Extension publication: herbicide resistance in vegetable production - how and why; and management options (herbicide and crop rotations, using non-herbicide weed control methods, and the importance of controlling survivors).	5.1.5; 6.2.3	Medium	Medium	***Medium***
Minor Use Herbicide Permits				
Extension topic: the application process and benefits of the minor use program for chemical permits.	6.2.4	High	High	***High***
Development and extension topic: streamlining the minor use program.	5.1.4	High	Medium-Low	***Medium***
Promoting Integrated Weed Management				
Extension publication: Integrated Weed Management for the Australian vegetable industry (hard copy, online, and/or smartphone app).	5.3.1; 6.2.1	Medium-High	Medium-High	***High***
Promoting integration of efficient herbicide use with other weed control techniques to improve herbicide sustainability.	5.1.6, 6.2.3	Medium-High	Medium	***Medium***
Promoting the benefits of herbicide rotations and crop rotations - examples, major weeds controlled, rotation to non-vegetable crops where feasible.	4.1; 6.2.4	High	Medium	***Medium***
Extension message/publication: the benefits of farm hygiene for weed control.	4.4.7	Medium	High	***Medium***
Decision Support Tool				
The feasibility and potential benefits of developing a decision support tool for vegetable crop protection.	5.3.2	Low-Medium	Low	***Low***

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Attachment 1: Current Weed Management Chemicals

Table A1 Herbicides currently registered for use in Australian vegetable crops

Chemical AI	Chemical Name/s	Group	Crops	Examples of Weeds Controlled	Timing	Australian Distributor
Atrazine	Gesaprim	C	Sweet corn, potatoes	Amaranthus, blackberry nightshade, caltrop, cobbler's pegs, milk thistle, fat hen, pigweed, potato weed, prickly melon, wild oats, wireweed	Pre-plant, pre-emergence or post-emergence	Syngenta
Bentazone	Basagran; Dictate 480	C	Beans	Fat hen, potato weed, groundsel, purslane/pigweed, shepherd's purse, cobbler's pegs, thornapple, blackberry nightshade, wild radish	Post-emergence	BASF; Crop Care
Bromacil	Hyvar X	C	Asparagus	Ryegrass, Bathurst burr, caltrop, capeweed, cobbler's pegs, doublegee, Paterson's curse, summer grass, thornapple, wild mustard, wild oats, wild radish, winter grass	Plants older than 1 year	Dupont
Carfentrazone	Nail	G	Non-selective	Non-selective	Non-selective	Crop Care

Table A1 Continued

Chemical AI	Chemical Name/s	Group	Crops	Examples of Weeds Controlled	Timing	Australian Distributor
Chloridazon	Pyramin	C	Red beet, silver beet	Blackberry nightshade, capeweed, chickweed, milk thistle, fat hen, marshmallow, pigweed, potato weed, shepherd's purse, wild radish, winter grass.	Post-sowing pre-emergent	BASF
Chlorthal-Dimethyl	Dacthal 900 WG	D	Brassicas, Beans, Peas, Garlic, Onions, Carrots, Lettuce, Potatoes, Turnips	Nutgrass, barnyard grass, blackberry nightshade, caltrop, capeweed, chickweed, fat hen, pigweed, amaranth, ryegrass, stinging nettle	At time of seedling or transplanting.	Crop Care
Clethodim	Havoc; Sequence; Status	A	Beetroot, Cabbage, Celery, Lettuce, Potatoes, Onions	Grasses e.g. Barnyard grass, Johnson grass, annual ryegrass, wild oats, volunteer cereals, winter grass	Pre-plant	Crop Care; Nufarm; Sumitomo
Clomazone	Command 480 EC; Director	F	Cucurbits, potatoes	Blackberry nightshade, fat hen, potato weed, amaranth	Post-plant pre-emergence	FMC; Crop Care
Cyanazine	Bladex 900 WG	C	Onions, peas, potatoes, sweet corn	Blackberry nightshade, chickweed, milk thistle	Post-plant pre-emergence or early post-emergence, but depends on crop type	AgNova
Dicamba	Cadence	I	Potatoes	Blackberry nightshade, chickweed, fat hen, wireweed, thistles	Apply after haulm senescence	Syngenta

Table A1 Continued

Chemical AI	Chemical Name/s	Group	Crops	Examples of Weeds Controlled	Timing	Australian Distributor
Dimethenamid-P	Frontier-P	K	green beans, navy beans, sweet corn, corn, poppies, green peas, pumpkins and kabocha	Apple of Peru, fat hen, blackberry nightshade, milk thistle, shepherd's purse, ryegrass, white clover, pigweed	At or immediately after sowing; pre-emergent	BASF
Diquat	Reglone	L	Non-selective	Non-selective	Non-selective	Syngenta
Diuron	Diurex WG	C	Asparagus, Peas	Amaranthus, capeweed, cobbler's pegs, fat hen, milk thistle, pigweed, summer grass, wild oats, wild radish, wild turnip	Pre-emergence	Crop Care
EPTC	Eptam	E	Beans, potatoes	Barnyard grass, summer grass, wild oats, winter grass, amaranth, blackberry nightshade, chickweed, fat hen, giant pigweed, pigweed, shepherd's purse, nutgrass	Pre-emergent	Crop Care
Ethofumesate	Tramat	K	Beets, onions	chickweed, cleavers, fat hen, fumitory, amaranthus, shepherd's purse, wireweed	Pre- or post-emergent depending on crop	Bayer CropScience
Fluazifop-P-Butyl	Fusilade	A	Broad Beans, Broccoli, Brussel Sprouts, Cabbage, Capsicums, Carrots, Cauliflower, Celery, Green Beans, Lettuce, Tomatoes, Peas, Onions, Potatoes, Cucurbits	Grasses e.g. Barnyard grass, Johnson grass, annual ryegrass, couch grass, wild oats, volunteer cereals	Post-emergent	Syngenta
Glufosinate-Ammonium	Basta; Biffo	N	Tomatoes	Non-selective	Used in tomatoes as a shielded inter-row spray	Bayer CropScience ; Crop Care

Glyphosate	Weedmaster Agro; Weedmaster Duo; Gladiator	M	Non-selective	Non-selective	Non-selective	Nufarm; Crop Care

Table A1 Continued

Chemical AI	Chemical Name/s	Group	Crops	Examples of Weeds Controlled	Timing	Australian Distributor
Ioxynil	Totril	C	Onion	Capeweed, chickweed, milk thistle, fat hen, pigweed, potato weed, shepherd's purse, marshmallow, wild radish, wireweed	Post-emergence	Bayer CropScience
Linuron	Linuron DF and flowable	C	Carrots, parsnips, onions, potatoes	Amaranth, blackberry nightshade, capeweed, chickweed, milk thistle, fat hen, marshmallow, potato weed, pig weed, stinging nettle	Pre- or post-emergent depending on crop	AgNova
Methabenzthiazuron	Tribunil	C	Onions	Capeweed, chickweed, fat hen, fumitory, London rocket, mallow, potato weed, amaranthus, pigweed, milk thistle, winter grass, wild radish	Post-emergent (one or more true leaves in onion crop	AgNova
Metham	Metham sodium; Tamafume (fumigants)	N/A	All crops	Winter grass, amaranth, fat hen		Nufarm
Metribuzin	Sencor; Tomahawk	C	Asparagus, Peas, Potatoes, Tomatoes	Thornapple, chickweed, shepherd's purse, fat hen, capeweed, chickweed, stinging nettle, milk thistle, pigweed, blackberry nightshade	Pre-emergence	Bayer CropScience ; Crop Care
N/A	Degerminator Bioherbicide	N/A	All crops	Aims to degrade weed seed protective coating, rendering seed unviable for germination		Earthlife
Norflurazon	Zoliar	F	Asparagus	Johnson grass, nutgrass	Pre-emergence	Syngenta

Table A1 Continued

Chemical AI	Chemical Name/s	Group	Crops	Examples of Weeds Controlled	Timing	Australian Distributor
Oxyfluorfen	Baron 400 WG; Goal; Striker	G	Brassicas	Barnyard grass, blackberry nightshade, caltrop, capeweed, chickweed, fat hen, pigweed, amaranthus, ryegrass, shepherd's purse, mallow, soursob, milk thistle, wild radish, wireweed, stinging nettle, potato weed	Pre-transplant (7 days prior)	AgNova; Dow AgroScience ; Nufarm
Paraquat	Gramoxone; Nuquat 250	L	Non-selective	Non-selective	Non-selective	Syngenta; Nufarm
Paraquat and Diquat	Spray.Seed 250; Revolver	L	Non-selective	Non-selective	Non-selective	Syngenta; Nufarm
Pendimethalin	Rifle 440; Romper; Stomp 330EC; Stomp 440; Stomp Xtra	D	Carrots, peas, beans, onions, transplanted broccoli, cabbage, cauliflower and processing tomatoes	chickweed, fat hen, milk thistle, pigweed, shepherd's purse, wireweed, nettles, blackberry nightshade, fumitory, wild radish, winter grass	Pre-emergence	Nufarm; Crop Care; BASF
Phenmedipham	Betanal Flow 160 SE	C	Beetroot and silverbeet	Fat hen, chickweed, potato weed, pigweed, thornapple, bell vine, groundsel, milk thistle, shepherd's purse, fumitory, amaranthus, winter grass, blackberry nightshade	Post-emergence selective	Bayer CropScience
Prometryn	Gesagard; Prometryn 900DF	C	Carrots, celery, potatoes	Amaranth, blackberry nightshade, capeweed, chickweed, fat hen, annual ryegrass, barnyard grass, pigweed, potato weed	Pre-emergent, or early post-emergent in carrots	Syngenta; Nufarm

Table A1 Continued

Chemical AI	Chemical Name/s	Group	Crops	Examples of Weeds Controlled	Timing	Australian Distributor
Propachlor	Ramrod	K	Onions, transplanted brassicas, beetroot	Annual ryegrass, barnyard grass, chickweed, fat hen, fleabane, milk thistle, amaranth, shepherd's purse, stinging nettle, winter grass, wireweed, pigweed, potato weed	Pre-emergence, pre-transplant or at-transplant, depending on crop.	Nufarm
Propyzamide	Kerb 500 SC	D	Lettuce (sown and transplanted)	Barnyard grass, Summer grass, Winter grass, Rye grass, Portulaca, Prince of Wales feather, Blackberry nightshade, Chickweed, Nettles, Shepherd's purse and Wireweed	Pre-emergent, or immediately after transplantwith irrigation after application	Dow AgroScience
Prosulfocarb and S-metolachlor	Boxer Gold	J, K	Potatoes	Grasses including ryegrass	Apply after planting, after the first cultivation but no later than 25% potato shoot emergence	Syngenta
Rimsulfuron	Titus	B	Tomato	Blackberry nightshade, caltrop, paddy melon, heliotrope	Post-emergence	Dupont
S-Metolachlor	Dual Gold	K	Brassicas, beans, sweet potatoes	Blackberry nightshade, fat hen, pigweed, potato weed, stinging nettle, wireweed, milk thistle, ryegrass, shepherd's purse	Immediately after transplanting	Syngenta
Shirquat	Shirquat	L	Non-selective	Non-selective	Non-selective	Crop Care
Simazine	Gesatop; Simagranz	C	Asparagus	Amaranthus, chickweed, capeweed, milk thistle, fat hen, nettles, potato weed, shepherd's purse, thistles, wild radish	Pre-emergence	Syngenta; Crop Care
Trifluralin	Treflan; Trifluralin	D	Peas, brassicas (transplanted and direct seeded),	Grasses e.g. Annual ryegrass, barnyard grass, wild oats and winter grass, as well as wireweed, pigweed	Pre-plant	Dow AgroScience ; Crop Care

			tomatoes, carrots	and amaranthus			

Table A2 Minor use herbicide permits for Australian vegetable crops, June 2014

Chemical AI	Chemical Name	Group	Crops	Weeds controlled	Permit Expiry Date	States	Australian Distributor
Bentazone-sodium	Basagran; Dictate 480	C	Snow peas and sugar snap peas	Broadleaf weeds	31/03/2015	All states (except Vic)	BASF; Crop Care
Bentazone-sodium	Basagran; Dictate 480	C	Green Peas (processing)	Broadleaf weeds	30/09/2014	Tas	BASF; Crop Care
Chlorthal-dimethyl	Dacthal 900 WG	D	Parsley	Various broadleaf weeds and grasses	31/03/2023	All states (except Vic)	Crop Care
Chlorthal-dimethyl	Dacthal 900 WG	D	Lettuce	Stinging nettle	31/08/2016	SA & WA only	Crop Care
Clethodim	Havoc; Sequence; Status	A	Radish	Grass Weeds	30/09/2016	All states	Crop Care; Nufarm; Sumitomo
Clethodim	Havoc; Sequence; Status	A	Carrots	Grass weeds, including winter grass	31/03/2019	All states (except Vic)	Crop Care; Nufarm; Sumitomo
Clethodim	Havoc; Sequence; Status	A	Parsnip	Grass Weeds	31/03/2022	All states (except Vic)	Crop Care; Nufarm; Sumitomo
Clethodim	Havoc; Sequence; Status	A	Peas (green & processing), Eggplant or Aubergine, Chilli peppers, Paprika, Silverbeet & Spinach	Annual ryegrass & winter grass that are resistant to quizalafop herbicides	31/12/2016	All states (except Vic)	Crop Care; Nufarm; Sumitomo
Clethodim	Havoc; Sequence; Status	A	Brassica Vegetables (Broccoli, Brussel sprouts & cauliflower)	Ryegrass & winter grass	30/06/2017	All states (except Vic)	Crop Care; Nufarm; Sumitomo
Clethodim	Havoc; Sequence; Status	A	Brassica Leafy	Grass Weeds	30/09/2015	All states	Crop Care;

			Vegetables, Chicory, Endive & Radicchio			(except Vic)	Nufarm; Sumitomo

Table A2 Continued

Chemical AI	Chemical Name	Group	Crops	Weeds controlled	Permit Expiry Date	States	Australian Distributor
Clethodim	Havoc; Sequence; Status	A	Spring Onions, Leeks and Shallots	Grass Weeds	31/03/2017	All states (except Vic)	Crop Care; Nufarm; Sumitomo
Clethodim	Havoc; Sequence; Status	A	Rhubarb	Grass weeds listed on label	30/06/2019	All states (except Vic)	Crop Care; Nufarm; Sumitomo
Clethodim	Havoc; Sequence; Status	A	Rhubarb	Grass weeds listed on label	30/06/2014	All states (except Vic)	Crop Care; Nufarm; Sumitomo
Clopyralid	Lontrel	I	Cauliflower	Capeweed and Clover	30/09/2016	WA	Dow AgroScience
Cyanazine	Bladex 900 WG	C	Leeks & garlic	Specified Grass and Broadleaf Weeds	1/10/2015	All states (except Vic)	AgNova
Cyanazine	Bladex 900 WG	C	Snow peas and sugar snap peas	Broadleaf weeds	31/03/2015	All states (except Vic)	AgNova
Diflufenican	Brodal Options	F	Peas	Broadleaf weeds	31/03/2023	All states (except Vic)	Bayer CropScience
Ethofumesate	Tramat	K	Spinach (*Spinacia oleracea* only), Silverbeet	Various Weeds	31/07/2014	All states (except Vic)	Bayer CropScience
Ethofumesate	Tramat	K	Leeks & garlic	Specified Grass and Broadleaf Weeds	4/10/2015	All states (except Vic)	Bayer CropScience
Ethofumesate	Tramat	K	Beetroot & Onions	Grass weeds	30/06/2015	Tas	Bayer CropScience

Table A2 Continued

Chemical AI	Chemical Name	Group	Crops	Weeds controlled	Permit Expiry Date	States	Australian Distributor
Fluazifop-p-butyl	Fusilade	A	Parsley, coriander, brassica leafy vegetables, chicory, endive, radicchio, spinach, silverbeet, turnip, swede	Annual Grass Weeds	30/06/2016	All states (except Vic)	Syngenta
Fluazifop-p-butyl	Fusilade	A	Various root vegetables (Taro, Rakkyo, Daikon, Brdock, Yam, Yam bean, Lotus root, water chestnuts, Galangal & Turmeric	Grass weeds, including couch and guinea grass (as listed on product label)	31/12/2016	All states (except Vic)	Syngenta
Fluazifop-p-butyl	Fusilade	A	Eggplant, Shallots, Spring onions, Leeks, Garlic, Parsnips & Sweet potato	Various Grass Weeds	31/03/2018	All states (except Vic)	Syngenta
Glyphosate	Weedmaster Agro; Weedmaster Duo; Gladiator	M	Parsley, coriander, brassica leafy vegetables, chicory, endive, radicchio, spinach, silverbeet, turnip, swede	Grass and broadleaf weeds (shielded sprayer)	30/06/2019	All states	Nufarm; Crop Care

Table A2 Continued

Chemical AI	Chemical Name	Group	Crops	Weeds controlled	Permit Expiry Date	States	Australian Distributor
Glyphosate	Weedmaster Agro; Weedmaster Duo; Gladiator	M	Carrots	Certain Broadleaf and grass weeds (shielded sprayer)	30/06/2015	All states (except Vic)	Nufarm; Crop Care
Glyphosate	Weedmaster Agro; Weedmaster Duo; Gladiator	M	Capsicums - Snow Peas - Sugar Snap Peas	Annual and Perennial Grass and Broadleaf Weeds (shielded sprayer)	30/06/2019	NSW, Qld	Nufarm; Crop Care
Ioxynil	Totril	C	Leeks & garlic	Specified Grass and Broadleaf Weeds	3/10/2015	All states (except Vic)	Bayer CropScience
Ioxynil	Totril	C	Spring onion, Shallot & Welsh onion	Broadleaf Weeds	31/03/2016	All states (except Vic)	Bayer CropScience
Linuron	Linuron	C	Parsnips	Broadleaf weeds	30/09/2015	All states (except Vic)	AgNova
Linuron	Linuron	C	Celery	Range of weeds	30/04/2017	All states (except Vic)	AgNova
Linuron	Linuron	C	Leeks & Celeriac	Grass and Broadleaf weeds	30/04/2016	Qld, NSW, SA, WA, Tas	AgNova
MCPA	MCPA	I	Rhubarb	Broadleaf weeds.	30/09/2016	All states	Dow AgroScience
Methabenzthiazuron	Tribunil	C	Leeks, Spring Onions and Shallots	Various broadleaf and grass weeds	30/06/2016	All states (except Vic)	AgNova
Methabenzthiazuron	Tribunil	C	Leeks, Spring Onions and Shallots	Various broadleaf and grass weeds	30/06/2014	All states (except Vic)	AgNova
Oxyfluorfen	Baron 400 WG; Goal; Striker	G	Leeks & garlic	Specified Grass and Broadleaf Weeds	5/10/2015	All states (except Vic)	AgNova; Dow AgroScience; Nufarm
Pendimethalin	Rifle 440; Romper; Stomp 330EC; Stomp 440; Stomp Xtra	D	Parsnip	Grasses and Broadleaf Weeds	31/03/2015	ACT, NSW, QLD, SA, TAS, WA only	Nufarm; Crop Care; BASF

Table A2 Continued

Chemical AI	Chemical Name	Group	Crops	Weeds controlled	Permit Expiry Date	States	Australian Distributor
Pendimethalin	Rifle 440; Romper; Stomp 330EC; Stomp 440; Stomp Xtra	D	Brassica leafy vegetables, Rocket	Various weeds (listed on label)	31/08/2018	All states (except Vic)	Nufarm; Crop Care; BASF
Pendimethalin	Rifle 440; Romper; Stomp 330EC; Stomp 440; Stomp Xtra	D	Spring Onions, Shallots & Radish	Various broadleaf and grass weeds	31/03/2023	All states (except Vic)	Nufarm; Crop Care; BASF
Pendimethalin	Rifle 440; Romper; Stomp 330EC; Stomp 440; Stomp Xtra	D	Leeks & garlic	Specified Grass and Broadleaf Weeds	6/10/2015	All states (except Vic)	Nufarm; Crop Care; BASF
Pendimethalin	Rifle 440; Romper; Stomp 330EC; Stomp 440; Stomp Xtra	D	Parsnip	Grasses and Broadleaf Weeds	31/03/2015	All states (except Vic)	Nufarm; Crop Care; BASF
Pendimethalin	Rifle 440; Romper; Stomp 330EC; Stomp 440; Stomp Xtra	D	Brussel sprouts	Grasses and Broadleaf Weeds	30/06/2019	All states (except Vic)	Nufarm; Crop Care; BASF
Pendimethalin	Rifle 440; Romper; Stomp 330EC; Stomp 440; Stomp Xtra	D	Horseradish	Annual grasses and Broadleaf weeds as per label	30/06/2015	All states (except Vic)	Nufarm; Crop Care; BASF
Phenmedipham	Betanal Flow 160 SE	C	Lettuce, chicory, endive, radicchio, spinach, & baby spinach	Broadleaf weeds	31/12/2015	All states (except Vic)	Bayer CropScience
Phenmedipham	Betanal Flow 160 SE	C	Lettuce, chicory, endive, radicchio, spinach, & silverbeet	Broadleaf weeds	30/06/2014	All states (except Vic)	Bayer CropScience
Prometryn	Gesagard; Prometryn 900DF	C	Parsnip	Weeds	30/09/2015	All states (except Vic)	Syngenta; Nufarm
Prometryn	Gesagard; Prometryn 900DF	C	Celeriac	Grass Weeds listed on Label	31/03/2017	All states (except Vic)	Syngenta; Nufarm

Table A2 Continued

Chemical AI	Chemical Name	Group	Crops	Weeds controlled	Permit Expiry Date	States	Australian Distributor
Prometryn	Gesagard; Prometryn 900DF	C	Taro, Daikon, Galangal, Burdock, Yam, Tumeric, Yam bean	Grass & Broadleaf weeds as per registered label	31/03/2019	All states (except Vic)	Syngenta; Nufarm
Prometryn	Gesagard; Prometryn 900DF	C	Carrots	Broadleaf weeds	30/09/2015	Qld	Syngenta; Nufarm
Propachlor	Ramrod	K	Radish, swede, turnip	Grass and Broadleaf weeds	31/12/2019	All states	Nufarm
Propachlor	Ramrod	K	Lettuce, spinach, silverbeet, rocket, Brassica leafy vegetables, spring onions and shallots	Annual grasses and broadleaf weeds	30/09/2015	All states (except Vic)	Nufarm
Propachlor	Ramrod	K	Leeks & garlic	Specified Grass and Broadleaf Weeds	2/10/2015	All states (except Vic)	Nufarm
Propyzamide	Kerb 500 SC	D	Artichoke (Globe)	Selected broadleaf and Grass weeds	30/11/2016	All States	Dow AgroScience
Propyzamide	Kerb 500 SC	D	Chicory & Endive	Grass and Broadleef weeds	30/04/2018	All states (except Vic)	Dow AgroScience
S-metolachlor	Dual Gold	K	Brassica Leafy Vegetables	Selected broadleaf and Grass weeds	31/03/2017	All States	Syngenta
S-metolachlor	Dual Gold	K	Rhubarb	Various weeds	31/08/2015	All states	Syngenta
S-metolachlor	Dual Gold	K	Silverbeet, Spring onions, Shallots, Green beans and Navy beans	Various broadleaf and grass weeds.	30/06/2017	All states (except Vic)	Syngenta

Table A2 Continued

Chemical AI	Chemical Name	Group	Crops	Weeds controlled	Permit Expiry Date	States	Australian Distributor
Simazine	Simazine 900 WG	C	Leeks & garlic	Specified Grass and Broadleaf Weeds	30/09/2015	All states (except Vic)	Titan Ag
Trifluralin	Treflan; Trifluralin	D	Parsnips	Winter Grass	31/03/2018	All states (except Vic)	Dow AgroScience ; Crop Care
Trifluralin	Treflan; Trifluralin	D	Swede, turnip	Annual grasses & Broadleaf weeds	30/06/2020	All states (except Vic)	Dow AgroScience ; Crop Care
Trifluralin	Treflan; Trifluralin	D	Peppers (including Capsicum, Chillies, Paprika) and Eggplant	Various Broad Leaf and Grass Weeds.	30/06/2021	All states (except Vic)	Dow AgroScience ; Crop Care

Weed Management for the Vegetable Industry:

Appendix 1 – literature review

Prepared for Horticulture Australia Limited (VG13079)

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August 2014

Table of Contents

1. Introduction 1
1.1. Background 1
1.2. Objectives 2
1.3. Methodology 2
1.4. Report structure 3
2. Vegetable production in Australia 4
2.1. Value, volume, area of vegetable production in Australia 4
2.2. Vegetables produced in Australia 4
2.3. Where vegetables are grown 5
2.4. Farm diversity 5
2.5. Domestic and export markets 6
3. Impact of weeds on vegetable production in Australia 7
3.1. Economic impact 7
3.2. Impact on crop yield 9
3.3. Impact on crop quality 11
3.4. Impact on crop and farm management 13
4. Important weeds in the industry 15
5. Current weed control approaches 22
5.1. Herbicides 22
5.1.1. Herbicide crop damage 23
5.1.2. Weed control success 24
5.2. Tillage/cultivation 24
5.2.1. Weed control success and viability 24
5.3. Hand weeding 26
5.3.1. Cost 26
5.4. Plastic mulch film 27
5.4.1. Weed control success and viability 28
5.5. Crop rotation 29
5.5.1. Weed control success and viability 29
5.6. Transported organic mulch 30
5.6.1. Weed control success and viability 30
5.7. Cover crop mulches 31
5.7.1. Weed control success and viability 31
5.8. Precision agriculture 33
5.8.1. Controlled traffic 33
5.8.2. Reduced till permanent or semi-permanent beds 34
5.9. Fumigation and biofumigation 35
5.9.1. Biofumigation using killed mulches 35
5.10. Crop competition 36
5.11. Farm hygiene 37
5.12. Stale and false seedbeds 37
5.12.1. Weed control success 38
5.13. Thermal weed control 39
5.13.1. Flaming 39
5.13.2. Steam 40
5.13.3. Soil solarization 40
5.14. Integrated weed management in Australian vegetable crops 40
5.14.1. The relationship of IWM to crop pest and disease management 42
5.14.2. The relationship of IWM to soil health 43

5.15. Organic weed management in Australian vegetable crops ... 43

6. Innovations in weed control in vegetable crops ... 46
6.1. Factors influencing weed control practice change ... 46
6.1.1. Herbicide resistance ... 46
6.1.2. Changing climate ... 47
6.1.3. Environmental impacts of herbicide ... 47
6.1.4. Plastic mulch disposal issues ... 48
6.1.5. Fumigation – an uncertain future ... 49
6.1.6. Socio-economic factors ... 49
6.1.7. Technological development ... 50
6.2. Herbicide options ... 50
6.3. Biodegradable mulch films ... 50
6.3.1. Polymer-based films ... 50
6.3.2. Paper-based films ... 51
6.3.3. Biodegradable weed mats ... 51
6.3.4. Australian field trials ... 52
6.4. Innovations in weed control outside Australia ... 53

7. Knowledge and research gaps ... 55
7.1. Gaps relating to the impact of weeds ... 55
7.1.1. Supporting vegetable production in the Top End ... 55
7.1.2. Economic impact analysis ... 55
7.2. Gaps relating to important weeds ... 56
7.3. Gaps relating to weed management practices ... 56
7.3.1. Herbicide availability ... 56
7.3.2. Herbicide resistance ... 57
7.3.3. Genetically modified vegetable crops ... 57
7.3.4. Hand weeding implements ... 57
7.3.5. Crop rotation ... 57
7.3.6. Biodegradable mulch film ... 58
7.3.7. Cover crop mulches ... 58
7.3.8. Controlled traffic farming ... 58

8. Lessons from other agricultural industries ... 60
8.1. Reduced or zero till systems ... 60
8.2. Genetically modified crops ... 60
8.3. Precision weed detection and control technology ... 60
8.4. Herbicide resistance management ... 61
8.5. Integrated Weed Management ... 61
8.6. Extension ... 62

9. Extension needs ... 64
9.1. Options for extension delivery ... 64
9.2. Preferred information sources ... 64
9.3. Currently available extension sources ... 65
9.3.1. One to one extension services – private and government ... 65
9.3.2. Regional and state farmer groups ... 65
9.3.3. Written and online services ... 66
9.4. HAL extension research and activity ... 67
9.5. Gaps in extension ... 68
9.5.1. Weed species ... 68
9.5.2. Current and innovative weed management methods ... 68
9.5.3. Integrated weed management ... 69
9.5.4. Weed impact ... 69

9.5.5. Declining government extension services 69

References 70

1. Introduction

1.1. Background

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. Effective crop protection against pests and diseases is economically important for vegetable producers, and crop losses can be high if associated weeds are not controlled (Coutts & Jones 2005, Blaesing 2013). In other parts of the world, weeds have been reported to cause greater economic losses for vegetable producers than pests and diseases. And yet despite this, relatively little R&D activity has been devoted in Australia to their management, with the plant health and crop protection focus predominately on insects and diseases (Blaesing 2013).

Weed control strategies vary between crops (Henderson & Bishop 2000). For example, slow-growing or long-season species require good bed preparation and on-going attention; small leaved and low stature crops are vulnerable to fast-growing, taller weeds; and sprawling crops make accessing weeds for control activities more difficult. Closely related weeds from the same botanical families as vegetable crops are particularly troublesome.

Good progress has been made for IWM in Australian broadacre grain and cotton crops in the last 20 years (McGillion & Storrie 2006, Charles 2013). But less attention has been paid to developing such weed control techniques in vegetables, despite limited earlier studies looking at experimental herbicides, organic mulches and brassica biofumigants (VG97063 - Weed management in pumpkins and other cucurbit crops) (Henderson 2000), biodegradable mulches (Limpus *et al.* 2012) and organic weed control methods (Kristiansen *et al.* 2007). 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 only applied to organic production (Thompson 2012). This is concerning given that the grains and cotton industries have demonstrated that IWM is key to the continuing productivity of conventional farmers. In contrast, the few producers who were using “high IWM” practices expressed support for investigating new IWM practices and technologies using R&D funds, a perception shared by consultants and research/extension personnel (Thompson 2012). The report by Chivers (2012) also highlights the value of alternative weed management methods and recommends research on farming systems approaches to weed management (equivalent to IWM) and novel technologies (e.g. thermal methods).

1.2. Objectives

The research questions to be addressed by this project are as follows.

1. Which weed species are causing greatest difficulty for vegetable farmers?

2. What methods are currently being used to control weeds in vegetable crops, and with what success?

3. What knowledge and research gaps exist for weed management in the vegetable industry?

4. What lessons can be learned and applied from other agricultural industries?

5. What are the research and extension needs of vegetable producers in relation to weed management?

These questions are being addressed by this literature review, a national survey of vegetable farmers, focus groups and farm visits in major vegetable producing regions across Australia, and key informant interviews. The findings from all stages of the project will be delivered to HAL in a final report.

1.3. Methodology

Weed impact and weed control issues, were explored through a review of Australian and international literature. Much of this review was is based on an earlier review of the literature completed as part of a cucurbit-specific research project (VG10048; Sindel *et al.* 2011). However, the review has been updated and expanded to include the variety of vegetable crops for this whole-industry scoping study, as well as the different research focus of this project.

Literature searches were conducted using the University of New England's library catalogue (printed publications and online documents available through several academic literature databases), the Google Scholar and Google search engines, and amongst the literature collection of the School of Environmental and Rural Science, University of New England.

The initial scope of the literature search was Australian academic literature (a key word search of relevant journals), with the search expanded to include relevant extension publications produced by various government departments across Australia. The HAL web site was searched for relevant reports, and these acquired either from HAL or from the authors. Other relevant web sites reviewed included the Council of Australian Weed Societies (where a library of Australian Weeds Conference papers is freely available), research organisations, AUSVEG, and the Australian Bureau of Statistics. Some unpublished reports and data were acquired from their authors, while a number of horticultural experts were consulted on specific points where literature could not be found, or was insufficient. International literature was also sourced for comparative purposes, to fill gaps in the review where Australian literature could not be found, or to identify weed control techniques not yet evaluated fully in Australia.

It became evident during the course of this review that there gaps in the existing knowledge of some aspects of weed impact and control in vegetable crops. This is reflected in the lack of academic publications in some sections of this review, and our reliance on extension publications and international literature sources. This strongly suggests a need for further research into a number of aspects of weed ecology, impact and control within Australian vegetable crops, both in the academic field and through industry-funded research. A research, development and extension plan that offers suggestions for filling these knowledge gaps, will be included in the final report for this project to address this need.

1.4. Report structure

Chapter 2 includes a summary of the value, volume and area of vegetable production in Australia, the main vegetable crops grown in Australia and where they are grown, and a discussion of domestic and international markets for Australian vegetables. In Chapter 3 we discuss the impact of weeds on vegetable production in Australia, including their economic impact, impact on yield and quality, and impact on farm management. In Chapter 4 we identify the weed species commonly found in Australian vegetable crops, presenting a list of these species and some examples of vegetable crops where they are problematic.

In Chapter 5 we identify the range of weed control techniques currently used by Australian vegetable farmers. These include herbicides, tillage/cultivation, hand weeding, plastic mulch film, crop rotation, transported organic mulch, cover crop organic mulch, precision agriculture, fumigation and biofumigation, crop competition, farm hygiene, stale and false seedbeds, and thermal weed control. The chapter includes a discussion of integrated weed management (IWM) in vegetable crops, the relationship of IWM to crop pest and disease management, and organic weed management approaches.

Chapter 6 includes a discussion of innovations in weed control, both within and outside of Australia. Some of the factors influencing weed control practice change are discussed, as are herbicide options, biodegradable mulch film, and innovations identified outside Australia. In Chapter 7, we discuss some of the apparent gaps in knowledge of and research about weed management in Australian vegetable crops, relating to weed impact, significant weed species, and weed management practices. Chapter 8 includes a discussion of innovative weed practices in other agricultural industries, particularly broadacre cropping, which may be worth exploring for their relevance to vegetable production. Finally in Chapter 9, we discuss the extension needs of vegetable farmers, including options for information delivery and preferred sources, currently available extension sources and services, and gaps in extension provision.

2. Vegetable production in Australia

2.1. Value, volume, area of vegetable production in Australia

Vegetables represent a significant economic sector of Australia's primary industries, with farm gate sale valued at about $3.6 billion in 2012-13. Domestic retail sales of vegetables have been estimated at over $7 billion annually. There were just over 6,000 vegetable farmers nationally in 2011-12, with over 1,600 in NSW, over 1,500 in Qld, nearly 1,000 in Victoria, approximately 600 each in South Australia, Western Australia and Tasmania, and over 80 in the Northern Territory. An area of over 126,000 hectares was planted under vegetables in 2011-12, with over 2.5 million tonnes of vegetables of all varieties produced (Freshlogic 2011; AUSVEG 2013a; Valle *et al.* 2014).

Vegetable production therefore comprises approximately 7 per cent of Australian agricultural production, which was valued at $46.7 billion in 2012 (ABS 2013). However, Table 2.1 below shows that Australia is responsible for only a very small proportion of world vegetable production (AUSVEG 2013a; FAO 2014).

Table 2.1 Australian vegetable production as a proportion of world production

	Australia 2011-12	World 2011-12	Australian Proportion (%)
Area (thousands of hectares)	126.41	58039.96	0.22%
Production (millions of tonnes)	2.57	1096.63	0.23%

Source: AUSVEG 2013a and FAO 2014. FAO data are available for 2011 and 2012 as separate years, hence an average figure for these two years has been used here for comparison with AUSVEG 2011-12 data for Australia. FAO figures include 'vegetables and melons'.

2.2. Vegetables produced in Australia

AUSVEG (2013a) data lists 47 distinct vegetable varieties produced commercially in Australia. Of these, the most valuable crops produced in 2011-12 included potatoes ($625.6 million), tomatoes ($351.8 million), mushrooms ($267 million), carrots ($215 million), onions ($212.5 million), and melons ($165.3 million).

Many vegetable crops are covered by the compulsory vegetable R&D levy. Funds raised under this levy are matched by the Australian Government to support targeted industry research. Some major vegetable crops including potatoes, processed tomatoes, onions and mushrooms are not included in the levy, having separate levy arrangements. Fresh tomatoes, melons, garlic and asparagus are not included in any levy scheme (AUSVEG 2012). Table 2.2 lists the vegetables included and excluded from the levy.

Table 2.2 Vegetable R&D levy – included and excluded vegetables

Leviable Vegetables	Vegetables Excluded from Levy
Carrots	Potatoes
Pumpkins	Potatoes – frozen
Sweet corn	Onions
Peas and beans	Tomatoes – processed
Lettuce	Tomatoes – fresh
Broccoli	Tomatoes – canned
Cauliflower	Asparagus
Capsicums	Mushrooms
Other vegetables	Other processed vegetables

Source: AUSVEG 2012.

2.3. Where vegetables are grown

Vegetables are produced in all Australian states and territories. The main growing regions in each state (Valle *et al.* 2014) include:

- New South Wales: the Greater Sydney region (particularly Hawkesbury/Richmond), the Murrumbidgee Irrigation Area, and the far north coast.
- Queensland: the Darling Downs, Lockyer Valley, Bowen, Bundaberg, and the Burdekin delta.
- South Australia: the Mallee, Murray Riverland, and Adelaide Plains.
- Tasmania: the northern coastal fringe and northern midlands.
- Victoria: the Greater Melbourne region (particularly Werribee and Cranbourne), Gippsland, and along the Murray River.
- Western Australia: along the coast north and south of Perth, the Carnarvon region and the Ord River irrigation area.
- Northern Territory: primarily in the Top End district surrounding Darwin and Katherine (NT Government 2010).

2.4. Farm diversity

On average, Australian vegetable farmers committed more than 50 per cent of their cropping area to vegetables in 2011-12 (33 hectares), and about 20 per cent of their total area of operations (166 hectares). Approximately 45 per cent of farmers produced more than one vegetable crop, with 8 per cent producing five or more crops. Vegetable farmers often hold diverse farming operations, with just under half of their cropping area on average being dedicated to other crops. Livestock production (beef cattle and sheep) is also common (Valle *et al.* 2014).

2.5. Domestic and export markets

The domestic market is supplied with over 3 million tonnes of locally produced vegetables annually, plus net imports (imports minus exports) of approximately 220,000 tonnes. Over 95% of locally produced processed and non-processed vegetables is supplied to the domestic retail and food service markets (Freshlogic 2011).

The export market for Australian vegetables is therefore small (approximately 5% of vegetables produced), so that Australian vegetable producers are primarily reliant on the domestic market for their income (Freshlogic 2011). Fresh, frozen and processed vegetables are exported. Fresh vegetables accounted for 61 per cent of total vegetable export value in 2012-13, at $151 million. Major fresh vegetable markets include Singapore and Japan, with most fresh vegetables being exported either to Asia or the Middle East. Carrots are the main fresh vegetable export, while other varieties include onions and shallots, potatoes, and asparagus. New Zealand is the main destination for frozen vegetables, with frozen prepared potatoes dominating frozen vegetable exports. Japan and New Zealand are the main destinations for processed vegetables, in the form of vegetable juices, tomato sauce, and potato and tomato products. Major export markets for other vegetable exports (primarily vegetable seed) include the Netherlands, Japan and France (AUSVEG 2013b).

3. Impact of weeds on vegetable production in Australia

Most vegetable crops in Australia are grown on intensively cropped land. Many vegetable farmers consider that weeds are manageable on their farm, and that pests, viruses and diseases are a more significant crop protection issue (Sindel *et al.* 2011). Despite this, the common features of vegetable cropping systems, including frequent cultivation that results in highly disturbed soil, irrigation (particularly furrow or flood irrigation), and the addition of large quantities of nutritional inputs before planting and during the growing period, mean that the potential for weed growth is high. When not managed effectively, weeds can have a significant impact on productivity (Henderson and Bishop 2000). The following sections summarise some of the impacts of weeds on vegetable production.

3.1. Economic impact

The economic impact of weeds in agriculture includes the costs of managing weeds, and associated yield losses, and has been estimated at around $4 billion annually across Australian agriculture (Sinden *et al.* 2004). In this section we focus on weed management expenses. Section 3.2 includes some examples of the yield reduction impacts of weeds. In Australian vegetable crops, weed management costs have been estimated to range from 2-22% of total variable expenses (Henderson and Bishop 2000).

Previous research suggests that vegetable farmers have considerable difficulty in providing reliable estimates of the cost of weed management within their crops, and that there is little data available (Kristiansen *et al.* 2007; Sindel *et al*. 2011; Blaesing *et al.* 2013). Estimates tend to vary considerably, depending on crop type and whether individual farmers are able to disaggregate and accurately take into account significant costs such as labour, cultivation, and plastic mulch. It is not always clear which farm operations are specifically associated with weed management. Similarly, it can be hard to disaggregate the costs and benefits of particular activities which may have a range of crop benefits in addition to weed control (such as use of plastic mulch film). Lack of recorded information on crop inputs also makes it difficult for many farmers, as well as policy makers, to estimate the economic burden of weed management (Kristiansen *et al.* 2007; Sindel *et al.* 2011).

In a case study of PMG Agriculture's watermelon and pumpkin farm near Condobolin, NSW, Watt (2009) estimated the cost of weed control to be approximately $267/Ha for 133Ha of watermelons and 54Ha of pumpkins. This cost included weed control activities pre-plant and during the growing season.

Blaesing *et al.* (2013) produced an economic model to use in calculating the cost of weed, pest & disease control activities as part of overall production costs in vegetable crops. The model allows currently used production systems to be compared with alternative systems. However, the model does not yet appear to have been used to prepare gross margin budgets for vegetable crops. The NSW Department of Primary Industries (DPI) has prepared a number of gross margin budgets for vegetable crops, using the 'VegTool' computer software package that was developed specifically for gross margin budget calculation in the vegetable industry (NSW DPI 2009-2013). These budgets included several items related to weed control, such as ground and bed preparation (tillage and bed forming), herbicide application (pre- and post-emergent) and, where available, labour costs associated with chipping and weeding.

These have been used in Table 3.1 to calculate weed control costs as a proportion of all pre-harvest variable production costs for several vegetable crops with differing management systems. The table shows that per hectare weed costs vary considerably amongst vegetable crops, from 24.6 per cent for a sprinkler irrigated cabbage system (where weed control activities include pre-emergent herbicide application and labour costs associated with chipping and weeding) to 7 per cent for butternut pumpkin (ground and bed preparation, and herbicide application). Weed control in capsicum includes only 1.7 per cent of pre-harvest variable costs; however the cost of purchasing plastic mulch film has not been factored in. Weed management in lettuce crops has been estimated at 16.2 per cent of pre-harvest variable costs, however other research suggests they may be as high as 20 per cent (Qld DAFF 2010).

Labour comprises a very significant part of the weed control costs illustrated in Table 3.1, where this data is provided. Furthermore, labour costs will include ground and bed preparation activity, plastic mulch application and herbicide application in different vegetable crops. Labour therefore appears to be the most significant weed management cost, and is also the largest contributor to total cash costs for vegetable producers (Valle *et al.* 2014). Any labour efficiency gained in weed management will therefore be of considerable benefit to vegetable farmers.

Table 3.1 Weed control cost estimates per hectare – NSW 2009 and 2013

	Weed control operations	Total weed control costs	Total pre-harvest variable production costs	Weed control % of costs*
* Beetroot - processing	Ground preparation, pre- and post-emergent herbicide application	$230.18	$1,982.21	11.6%
Cabbages - sprinkler irrigation	Pre-emergent herbicide, chipping & weeding, other unspecified activities	$1,039.00	$4,228.00	24.6%
* Capsicum	Ground preparation, plastic mulch film laying (*excludes cost of plastic mulch film, which was not provided in the budget*)	$151.94	$9,003.99	1.7%
* Carrot	Cultivation and bed forming, pre- and post-emergent herbicide application	$165.36	$2,809.10	5.9%
Lettuce	Bed forming and labour costs - chipping & weeding	$1,164.38	$7,188.71	16.2%
* Pumpkin - butternut	Ground and bed preparation, pre- and post-emergent herbicide application	$120.86	$1,715.49	7.0%

Source: NSW DPI Gross Margin Budgets 2009 and 2013.

** Weed control total costs do not include labour costs. In these cases, the labour costs have not been disaggregated in the gross margin budgets according to different activities. Weed control costs would be higher if all associated labour costs were included.*

In addition to the direct costs of weed management, weeds impose an economic burden on farmers through their negative impacts on crop yield and quality, and the constraints they impose on farm management. These impacts are discussed in the following three sections.

3.2. Impact on crop yield

Weeds compete with vegetable crops for water, soil nutrients, and for light and space by shading the crop and restricting its development and eventual yield (Henderson and Bishop 2000). Weeds can impact negatively on soil health; at the same time, healthy soils may facilitate weed suppression in some circumstances (Blaesing *et al.* 2013). Weeds may also be significant consumers of soil moisture, with research showing that vegetable crops facing reduced weed pressure are more likely to succeed, even in conditions where adequate levels of irrigation are available (Brainard 2012).

Other yield impacts on vegetable crops associated with weed infestations include damage associated with weed control efforts (for example, herbicide drift or damage to crop roots from tillage), and difficulty harvesting all crop fruit where weed infestations are particularly dense (Sindel *et al.* 2011). For faster growing vegetable crops, where the crop canopy will eventually cover the crop beds, it is important to control weeds in the early crop stages, allowing the crop canopy to develop to the extent that it provides sufficient shade to make it more difficult for weeds to develop (Burt 2005; Dimsey 2009). Where the crop canopy takes longer to close, or never closes fully (for example onions or carrots). weeds will need to be managed within the crops rows throughout the life of the crop, to ensure that yield is not impacted too severely.

The literature suggests that weeds can have a large impact on yield, particularly if weed infestations are heavy during the early growth stages of the crop. Weeds are just one factor which can impact negatively on the yield of a crop, others including diseases (both below and above ground), and pests (such as insects). It has been estimated that weeds, diseases and pests together can result in a loss of anywhere between 10 and 70% of the crop pre-harvest. The actual impact will depending on crop type, pest type/s, soil and weather conditions, timing of infestation, and crop management decisions (Blaesing *et al.* 2013).

Some vegetable crop systems may be more prone to weed invasion, where the crop plants are poorly equipped to compete with weeds (crop competition is covered in Section 5.10), or where plastic mulch film is not used (plastic mulch film is covered in Section 5.4). For example, yield losses of more than 90% have been found in carrot crops where weed control activities are not undertaken. Carrot plants are considered poorly equipped to compete with weed species (Swanton *et al.* 2009). A study conducted in Israel in muskmelon (rockmelon) crops suggested that weed-free plots yield between 2.7 and 3.3 times as much as weed-infested plots. Impact on yield during fruit development and maturation included both fruit weight and, to a lesser degree, fruit quantity (Nerson 1989).

Weeds may impact both on the *absolute yield* of a vegetable crop, as well as on its *marketable yield*. A trial in broccoli crops found that the presence of one fat hen (*Chenopodium album*) plant per 10.7 square feet of the crop reduced the total yield by 18-20%, but reduced marketable yield by 22-37%, mainly by reducing the head weight of the broccoli (Batts *et al.* 2008).

Crop stage is also a factor in whether weeds are able to impact on vegetable crop yield. For example, late emerging weeds may not impact significantly on yield within lettuce crops, whereas weeds may have a significant impact on lettuce crop yield if not controlled adequately in the early stages of the crop (Qld DAFF 2010; Vic DEPI 2013). Nevertheless, it is important to control weeds throughout the life of the lettuce crop. Crop yield reductions of approximately 25% were found in lettuce plots where no weeding was undertaken, compared to plots where effective hand weeding was undertaken (Kristiansen *et al.* 2008).

Poorly managed weed outbreaks in fields during fallow periods may also reduce the yield of subsequent vegetable crops. Weeds extract moisture and nutrients from the soil at these times, making investment in fallow weed control particularly important (GRDC 2012).

Finally, weeds have an indirect impact on crop yield through crop damage associated with herbicide use. This is discussed in more detail in Section 5.1.1.

3.3. Impact on crop quality

Weeds can host pests and diseases that impact on both the yield and the quality of vegetable crops (Henderson and Bishop 2000; McDougall 2011). Pest or disease infestations often start in a small area of a crop, or in an adjacent weed infestation (NT Department of Resources 2012). Weed management is therefore an important part of an 'integrated crop protection' program for vegetable production, which involves combining 'chemical, cultural (such as farm management practices), and biological methods to keep weeds, insect pest numbers, disease pressure, and other crop production problems low enough to prevent significant economic loss' (Blaesing *et al.* 2013; see also Vic DEPI 2013).

Weeds are capable of hosting a range of viruses, particularly broadleaf weeds that share certain characteristics with crop plants. For example in Western Australia, five principal viruses have been found infecting cucurbit crops. These include Zucchini yellow mosaic virus, papaya ringspot virus, squash mosaic virus, watermelon mosaic virus, and cucumber mosaic virus. These viruses infect wild or native cucurbits, which are considered weeds in cucurbit crops. They may also infect common weeds such as common sowthistle (*Sonchus oleraceus*), bifora (*Bifora testiculata*), prickly lettuce (*Lactuca serriola*), Indian hedge mustard (*Sisymbrium orientale*), and *Medicago* spp. When these weeds are not sufficiently controlled, they may act as 'infection reservoirs' for virus spread within cucurbit crops. Weeds can also provide a 'bridge' for viruses to persist in or near a field between crop growing seasons (Coutts 2006; Aftab *et al.* 2010; Coutts and Kehoe 2010; Sindel *et al.* 2011).

The majority of viruses are spread within the crop, or from weeds to crops, by insect pests (Qld DEEDI n.d.). Management of these viruses therefore includes insect pest control, effective farm hygiene, rigorous control of potential host weeds (including headlands and other crop area edges), and removal of old crops (vegetablesWA n.d., Grattidge *et al.* 2001; Coutts and Jones 2005; Napier 2009; McDougall 2011). It is important to control weeds that host both viruses, and the insect pests that spread these viruses to vegetable crops (Vic DEPI 2013).

High incidence of disease in a vegetable crop results in quality downgrades, rendering the crop either less likely to be sold, or likely to be sold at a downgraded quality. Impacts on the quality of crops include 'knobbles' or mottled skin on the fruit, discolouration, and reduced shelf-life. The main impact on yield is a shortened harvesting period, where the worsening effects of a virus render the fruit no longer worth harvesting (Coutts and Jones 2005).

Aphids of several varieties attack most vegetable crops. These include Currant lettuce aphid (CLA, *Nasonovia ribis-nigri*), Green peach aphid (GPA, *Myzus persicae*), Potato aphid (*Macrosiphum euphorbiae*), Corn aphid (*Rhopalosiphum maidis*), and Cabbage aphid (*Brevicoryne brassicae*) (vegetablesWA n.d.). Weeds known to host aphids include common sowthistle (*Sonchus oleraceus*), chicory and endive (*Cichorium* spp.), prickly lettuce (*Lactuca serriola*), nipplewort (*Lampsana* spp.), hawksbeard (*Crepis capillaris*), hawksweed (*Hieracium* spp.), and speedwell (*Veronica* spp.) (McDougall and Creek 2011; Vic DEPI 2013). Weed control is therefore recommended around and within crops to reduce aphid numbers (Qld DEEDI n.d.). Direct impacts of aphids on vegetable plants may include stunting and distorting plant growth and causing plants to wilt and bud drop, resulting in poor flowering and fruiting. They may also colonise plant parts (for example, lettuce hearts and rosettes), making them unsaleable (vegetablesWA n.d.; McDougall and Creek 2011). In addition to their direct impacts on vegetable crops, aphids are the most common group of virus vectors or carriers. Crops impacted by these viruses include beans, brassicas, capsicum, carrot, celery, cucurbits, lettuce, sweet corn, sweetpotato, and tomato (Qld DEEDI n.d.).

Thrips (*Thrips* spp.) feed on the leaves, flowers and fruit of a range of vegetable crops. They are also a vector for viruses such as tomato spotted wilt virus (TSWV), which can reduce the yield of lettuce, tomato, capsicum and chilli crops. A number of weeds are capable of hosting thrips, including amaranth (*Amaranthus* spp.), capeweed (*Arctotheca calendula*), pigweed (*Portulaca* spp.), mallows (*Malvaceae* spp.), blue heliotrope (*Heliotropium amplexicaule*), fat hen (*Chenopodium album*), nightshades (*Solanum* spp.), Scotch thistle (*Onopordum acanthium*), and common sowthistle. TSWV can cause total crop loss (vegetablesWA n.d.).

Weeds are a potential source or host for many other diseases and pests. McDougall (2007) provides a thorough summary of diseases and pests that impact on vegetable crops, and the role of weeds in hosting these. However, some examples (vegetablesWA n.d; HAL 2003; AUSVEG 2007; McDougall 2007; Nagle 2008; Webb 2008; McDougall 2009; Watson and Napier 2009; Persley *et al.* 2010; Thompson 2011) are included in Table 3.2.

Table 3.2 Example pests, viruses and disease in Australian vegetable crops that may be hosted by weeds

Pest, virus or disease name and impacted crop/s
Capsicum chlorosis virus in capsicum crops
Several viruses hosted by cucurbit weeds in cucurbit crops such as zucchini
Lettuce necrotic virus, which is spread by green sowthistle aphids (*Hyperomyzus lactucae*) that survive in common sowthistle but not on lettuce plants
Powdery mildew (*Erysiphe heraclei*) in carrot and parsnip crops
Black leg (the fungus *Phoma lingam*) hosted by brassica weeds in related brassica crops such as broccoli and Chinese cabbage
Grey mould (*Botrytis cinerea*) in tomato, bean, capsicum, cucumber, brassica and lettuce crops
Gummy stem blight (*Didymella bryoniae*) in pumpkin and rockmelon crops
Fungal root rot (including *Pythium*, *Rhizoctonia* and *Fusarium*) in a variety of vegetable crops
Black root rot (*Thielaviopsis basicola*) in bean, carrot and lettuce crops (with common sowthistle aka milk thistle a known weed host of this fungus)
Dry leaf spot (*Xanthomonas camestris* pv. vitians) in lettuce crops
Cavity spot (*Pythium violae*), hosted by broadleaf weeds in carrot crops in Victoria and South Australia
Clubroot (*Plasmodiophora brassicae*) in brassica crops, and hosted by related weeds such as wild turnip and wild radish
White blister (*Albugo candida*) in brassica crops (with wild radish and wild turnip suspected hosts)
Snails and slugs (particularly at the edge of crops near weedy fencelines or paddock boundaries)
Cutworm in carrot crops
Vegetable weevil (*Listoderes difficilis*) in a range of vegetable crops, for example carrots, tomatoes, celery and potatoes
Rutherglen bug (*Nysius vinitor*), potentially contaminating lettuce crops
Mites (several species)
Silverleaf whitefly *(Bemisia tabaci*)

3.4. Impact on crop and farm management

Weeds have a range of implications for managers of vegetable crops. Dense infestations can reduce the effectiveness of insecticide applications, make it difficult to identify pests in the crop, jam harvesting and other equipment, or make harvesting much slower for human pickers (Henderson & Bishop 2000).

Paddock inspection and hand weeding within crops is often carried out by casual staff, particularly on large farms. Casual staff might have insufficient training to identify weeds that appear similar to the crop (for example paddy melon, *Cucumis myriocarpus*, which has a similar physical appearance to watermelon plants) (Watt 2009). Mistaken identification of weeds is also possible by farmers (e.g. Sindel *et al.* 2011), so that inappropriate weed management strategies may be implemented to address a particular species, resulting in sub-optimal control.

Some vegetable crops present a more significant and ongoing weed management challenge to farmers than others. For example, some crops such as carrots, cabbage and sugar beets may achieve closure of the crop canopy relatively early in the growing period, resulting in effective suppression of weeds within the crop rows until harvest. Other crops, such as direct-sown onion and leek, are unlikely to achieve canopy closure at any stage during the crop. As a result, more extensive weed management is necessary up until harvest to ensure that significant crop losses do not occur. These crops are therefore the most technically and economically challenging for farmers to keep weed free. For many farmers, hand weeding within the crop rows is therefore a sizeable financial burden (Melander *et al.* 2005).

The presence of some weed species, particularly in large populations in the seedbank, may limit the vegetable crop choices available to farmers. It may also mean that vegetables cannot be grown economically on the farm, so that lower value crops are the only option available to farmers. For example, large populations of nut grass (*Cyperus rotundus*) or potato weed (*Galinsoga parviflora*) may make it impossible to grow a lettuce or brassica crop, at least without extensive management of the field for weeds over at least two years, which may involve cover cropping and/or crop rotation (Qld DAFF 2010; 2013). Dense nut grass infestations may mean that farmers choose to use infested fields for other, non-vegetable crops, or for grazing. This weed can make managing a high value vegetable crop economically unviable, and may interfere with plastic mulch retrieval after harvest, given its capacity to pierce the mulch film (Sindel *et al.* 2011).

Weeds that compete strongly with vegetable crops may cause difficulties during harvest, by interfering with harvesting equipment or making harvesting much slower for human pickers, particularly in the case of more mature infestations, or weeds that have sharp burrs or spines (Sindel *et al.* 2011). Vegetable crops are at a particular competitive disadvantage with weeds in the first few weeks after emergence before the crop canopy develops (Lonsbary *et al.* 2003). As discussed above, some crops will remain at a competitive disadvantage with weeds until harvest, in cases where the crop canopy never closes.

Weed management, particularly for broadleaf weeds after crop emergence, is made difficult for farmers by the lack of registered herbicides for controlling weeds within the crop rows. For many vegetable crops, such weeds are difficult to control with herbicides without causing significant damage to the crop, so that use of plastic mulch, precision shallow cultivation in the early post-emergence stage of the crop, or hand weeding once the crop plants have started to grow, are often the only realistic options for farmers. These techniques are discussed further in Chapter 5.

4. Important weeds in the industry

The most important weeds for Australian vegetable farmers will vary from one growing region to another, depending on climate and soil conditions and current weed distribution, while the relative impact of weeds within regions may also vary from one district or property to the next, based on a range of factors including crop type, farmer weed control dedication and diligence, diversity of methods used (van der Meulen *et al.* 2006a), and crop management system used. For example, farmers using a crop cover mulch are likely to face a different set of weed issues to those using polyethylene mulch, or those who do not mulch the crop beds. Certain cropping rotations will favour (or disadvantage) specific weeds, by interfering with the timing of their life cycle, and the availability of soil, water and nutrients. Planting crops that are related to the dominant weeds (for example, a broadleaf crop in a field with a history of producing broadleaf weeds) can restrict management options. Farmers producing crops that form a dense canopy are likely to have a less significant weed management issue than those who do not.

Weeds that have certain traits or characteristics may be more difficult to manage. These traits include: precocity (early seeding); fecundity (high rates of seed production); seeds that persist in the soil; seeds that are easily dispersed; weeds that are of the same family as crops (restricting or eliminating selective herbicide options); weeds that are tolerant of or resistant to herbicides (for example due to their leaf characteristics); and weeds that have persistent roots or rhizomes (making cultivation or tillage a less effective or even counter-productive management option, and perhaps meaning that herbicides are not translocated effectively) (Booth *et al.* 2003; Hawes *et al.* 2010; Navas 2012).

Table 4.1 lists broadleaf weeds that are mentioned in the literature as existing in Australian vegetable crops, Table 4.2 lists grass and sedge weeds, and Table 4.3 lists herbaceous weeds. These lists come from a number of sources, and may not be comprehensive. Some of these weeds may be problematic within the crop, while others may act as disease or virus hosts in areas in or near the crop rows (e.g. vegetablesWA n.d.; Coutts 2006; Aftab *et al.* 2010).

Table 4.1 Broadleaf weeds in Australian vegetable crops

Weed botanic and common name	Examples of vegetable crops impacted by weed	Literature source/s
Ageratum houstonianum (Blue billygoat weed or blue top)	cucurbits; lettuce; artichoke	Sindel et al. 2011; Qld DAFF 2012
Amaranthus powellii (amaranthus)	cucurbits; lettuce, tomato, capsicum, chilli; beans; sweet corn; peas; brassicas	vegetablesWA n.d.; Henderson and Bishop 2000; Batts et al. 2008; Nagle 2008; Serve-Ag 2008; Sindel et al. 2011; Qld DAFF 2013
Amaranthus viridis (green amaranth)	cucurbits; lettuce, tomato, capsicum, chilli; beans; sweet corn; peas; brassicas	vegetablesWA n.d.; Wright 2000; Sindel et al. 2011; Qld DAFF 2013
Arctotheca calendula (capeweed)	lettuce, tomato, capsicum, chilli	vegetablesWA n.d.
Bidens pilosa (farmer's friend or cobbler's pegs)	cucurbits; lettuce; artichoke; brassicas	Qld DAFF 2010; Sindel et al. 2011; Qld DAFF 2012; Qld DAFF 2013
Billardiera heterophylla (Bluebell creeper)	cucurbits	Sindel et al. 2011
Brassica tournefortii (wild turnip)	cabbage; cauliflower; broccoli; brussels sprouts; Chinese cabbage	AUSVEG 2007; Qld DAFF 2012
Capsella bursa-pastoris (Shepherd's purse)	cucurbits; lettuce; artichoke	Qld DAFF 2010; Sindel et al. 2011; Qld DAFF 2012
Chamaecrista rotundifolia (Wynn cassia)	cucurbits	Sindel et al. 2011
Chenopodium album (fat hen)	brassicas; cucurbits; lettuce, tomato, capsicum, chilli; beetroot; onion; potato	vegetablesWA n.d.; Henderson and Bishop 2000; Serve-Ag 2008; Qld DAFF 2010; Sindel et al. 2011; Qld DAFF 2012; Qld DAFF 2013
Chenopodium melanocarpum (Black crumbweed)	cucurbits	Sindel et al. 2011
Cichorium spp. (chicory and endive)	beans, brassicas, capsicum, carrot, celery, cucurbits, lettuce, sweet corn, sweetpotato, tomato	McDougall and Creek 2011
Citrullus lanatus (Afghan melon)	cucurbits	Coutts 2006; Sindel et al. 2011
Convolvulus spp. (bindweed)	beetroot; cucurbits; lettuce, tomato, capsicum, chilli; beans; sweet corn; peas	vegetablesWA n.d.; Qld DAFF 2012
Conyza spp. (Fleabane)	cucurbits; lettuce; artichoke	Sindel et al. 2011; Qld DAFF 2012
Coronopus didymus (lesser swinecress)	lettuce; cabbage; cauliflower; broccoli; brussels sprouts; Chinese cabbage	DAFF 2010; DAFF 2012
Crepis capillaris (hawksbeard)	beans, brassicas, capsicum, carrot, celery, cucurbits, lettuce, sweet corn, sweetpotato, tomato	McDougall and Creek 2011
Crotalaria spp. (rattlepod)	peas; beans	Qld DAFF 2012

Table 4.1 - continued

Weed botanic and common name	Examples of vegetable crops impacted by weed	Literature source/s
Cucumis myriocarpus (paddy melon or wild melon)	cucurbits	Watt 2009
Datura spp. (thornapple)	cucurbits; tomato; potato; capsicum; eggplant; brassicas	Sindel et al. 2011; Qld DAFF 2012; Qld DAFF 2013
Emex australis (spiny emex)	rhubarb; sorrel	Qld DAFF 2012
Euphorbia drummondii (caustic creeper)	cassava	Qld DAFF 2012
Fumaria spp. (fumitory)	cucurbits; lettuce; brassicas	Macleod et al. 2000; Qld DAFF 2010; Qld DAFF 2013
Galinsoga parviflora (potato weed)	cucurbits; lettuce; artichoke; brassicas	Qld DAFF 2010; Henderson 2000; Nagle 2008; Serve-Ag 2008; Sindel et al. 2011; Qld DAFF 2012; Qld DAFF 2013
Gomphrena celosioides (gomphrena weed)	cucurbits	Nagle 2008
Heliotropium amplexicaule (blue heliotrope)	lettuce, tomato, capsicum, chilli	vegetablesWA n.d.
Hibiscus trionum (Hibiscus or bladder ketmia)	cucurbits; lettuce	Qld DAFF 2010; Sindel et al. 2011
Hieracium spp. (hawksweed)	beans, brassicas, capsicum, carrot, celery, cucurbits, lettuce, sweet corn, sweetpotato, tomato	McDougall and Creek 2011
Ipomoea plebeia (Bell vine)	cucurbits; sweetpotato; sweet corn	Henderson and Bishop 2000; Sindel et al. 2011; Qld DAFF 2012
Lactuca serriola (prickly lettuce)	cucurbits; lettuce	Coutts 2006; Qld DAFF 2010
Lamium amplexicaule (deadnettle)	lettuce; brassicas	Qld DAFF 2010; Qld DAFF 2013
Lampsana spp. (nipplewort)	beans, brassicas, capsicum, carrot, celery, cucurbits, lettuce, sweet corn, sweetpotato, tomato	McDougall and Creek 2011
Lepidium spp. (peppercress)	cucurbits; cabbage; cauliflower; broccoli; brussels sprouts; Chinese cabbage	Sindel et al. 2011; Qld DAFF 2012
Malvaceae spp. (mallow)	cucurbits; lettuce, tomato, capsicum, chilli; beans; sweet corn; peas; brassicas	vegetablesWA n.d.; Coutts 2006; Sindel et al. 2011; Qld DAFF 2013
Medicago spp. (burr medic, snail medic, barrel medic)	cucurbits; peas; beans	Aftab et al. 2010; Qld DAFF 2012
Nicandra physalodes (apple of Peru; wild hops)	cucurbits; tomato; potato; capsicum; eggplant; brassicas	Henderson 2000; Serve-Ag 2008; Wright 2000; Sindel et al. 2011; Qld DAFF 2012; Qld DAFF 2013
Nothoscordum gracile (onion weed)	onion; garlic; shallots	Qld DAFF 2012
Onopordum acanthium (Scotch thistle)	lettuce, tomato, capsicum, chilli	vegetablesWA n.d.

Table 4.1 - continued

Weed botanic and common name	Examples of vegetable crops impacted by weed	Literature source/s
Parthenium hysterophorus (parthenium)	lettuce; artichoke	Qld DAFF 2012
Physalis minima (Wild gooseberry)	cucurbits	Sindel et al. 2011
Plantago spp. (plantain)	cucurbits; tomato; capsicum; beans; sweet corn; peas	vegetablesWA n.d.
Polygonum aviculare (hogweed, knotweed or wireweed)	cucurbits; lettuce; rhubarb; sorrel; brassicas; beetroot; onion; potato	Henderson and Bishop 2000; Macleod et al. 2000; Qld DAFF 2010; Sindel et al. 2011; Qld DAFF 2012; Qld DAFF 2013
Portulaca spp. (pigweed or purslane)	cucurbits; lettuce, tomato, capsicum, chilli; brassicas	vegetablesWA n.d.; Nagle 2008; Qld DAFF 2010; Sindel et al. 2011; Qld DAFF 2013
Raphanus raphanistrum (wild radish)	cucurbits; lettuce; artichoke; brassicas	Macleod et al. 2000; AUSVEG 2007; Qld DAFF 2010; Sindel et al. 2011; Qld DAFF 2012
Rapistrum rugosum (turnip weed)	lettuce; cabbage; cauliflower; broccoli; brussels sprouts; Chinese cabbage	Qld DAFF 2010; Qld DAFF 2012
Riccinus communis (castor oil plant)	cucurbits; cassava	Sindel et al. 2011; Qld DAFF 2012
Rumex spp. (docks)	rhubarb; sorrel	Qld DAFF 2012
Salvia reflexa (Mintweed)	cucurbits	Sindel et al. 2011
Sesbania cannabina (Sesbania)	cucurbits	Sindel et al. 2011
Sinapsis arvensis (charlock or wild mustard)	not stated	Blaesing 2013
Sisymbrium orientale (Indian hedge mustard)	cucurbits; lettuce	Aftab et al. 2010; Qld DAFF 2010
Solanum elaeagnifolium (Silverleaf nightshade)	cucurbits	Sindel et al. 2011
Solanum spp. (devil's fig; blackberry nightshade; silverleaf nightshade)	cucurbits; lettuce; tomato; capsicum; potato; eggplant; chilli; beans; sweet corn; peas; brassicas	vegetablesWA n.d.; Henderson and Bishop 2000; Macleod et al. 2000; Wright 2000; Nagle 2008; Qld DAFF 2010; Sindel et al. 2011; Qld DAFF 2012; Qld DAFF 2013
Sonchus oleraceus (common sowthistle or milk thistle)	cucurbits; lettuce, tomato, capsicum, chilli; bean; carrot; artichoke; brassicas	vegetablesWA n.d.; Henderson and Bishop 2000; Aftab et al. 2010; Qld DAFF 2010; Sindel et al. 2011; Qld DAFF 2012; Qld DAFF 2013; Vic DEPI 2013
Stellaria media (Chickweed)	cucurbits; lettuce	Qld DAFF 2010; Sindel et al. 2011
Tetragonia tetragoniodes (New Zealand spinach)	cucurbits	Sindel et al. 2011

Table 4.1 - continued

Weed botanic and common name	Examples of vegetable crops impacted by weed	Literature source/s
Trianthema portulacastrum (giant pigweed)	cucurbits	Wright 2000
Tribulus terrestris (caltrop or cathead)	cucurbits	Watt 2009; Wright 2000; Sindel et al. 2011
Trifolium spp. (clover)	cucurbits; tomato; capsicum; beans; sweet corn; peas	vegetablesWA n.d.; Macleod et al. 2000
Urtica spp. (Nettles)	lettuce; brassicas; cucurbits	Henderson and Bishop 2000; Qld DAFF 2010; Qld DAFF 2013
Veronica spp. (speedwell)	beans, brassicas, capsicum, carrot, celery, cucurbits, lettuce, sweet corn, sweetpotato, tomato	McDougall and Creek 2011
Xanthium spinosum (Bathurst burr)	cucurbits	Sindel et al. 2011

Table 4.2 Grass and sedge weeds in Australian vegetable crops

Weed botanic and common name	Examples of vegetable crops impacted by weed	Literature source/s
Agropyron repens (English couch)	cucurbits	Pest Genie 2010
Agrostis spp. (bent grass)	cucurbits	Pest Genie 2010
Avena spp. (wild oats)	cucurbits	Pest Genie 2010
Axonus spp. (carpet grass)	cucurbits	Pest Genie 2010
Brachiaria milliformis (green summer grass)	cucurbits	Pest Genie 2010
Brachiaria mutica (Para grass)	cucurbits	Pest Genie 2010
Bromus spp. (brome grass)	cucurbits	Pest Genie 2010
Cenchrus longispinus (Sand burr)	cucurbits	Sindel et al. 2011
Chloris gayana (Rhodes grass)	cucurbits	Sindel et al. 2011
Cynodon spp. (couch grass)	cucurbits	Henderson and Bishop 2000; Wright 2000; Pest Genie 2010
Cyperus rotundus (nut grass)	cucurbits; lettuce; potato; Chinese water chestnuts	Henderson and Bishop 2000; Macleod et al. 2000; Sindel et al. 2011; Qld DAFF 2010; Qld DAFF 2012
Digitaria spp. (summer grass; crab grass)	cucurbits	Pest Genie 2010; Hidayat and Preston 2001
Echinochloa spp. (barnyard grass)	cucurbits; sweet corn	Henderson and Bishop 2000; Wright 2000; Pest Genie 2010; Sindel et al. 2011
Eleusine indica (crowsfoot grass)	cucurbits	Pest Genie 2010; Sindel et al. 2011
Eragrostis cilianensis (stinkgrass)	cucurbits	Pest Genie 2010
Eragrostis curvula (African lovegrass)	cucurbits	Sindel et al. 2011
Hordeum spp. (barley grass)	cucurbits	Pest Genie 2010; Watt 2009
Lolium rigidum (Wimmera or annual ryegrass)	cucurbits	Pest Genie 2010; Malone et al. 2010; Powles and Holtum 1990
Panicum maximum (Guinea grass)	cucurbits	Pest Genie 2010
Paspalum paspalodes (water couch)	cucurbits	Pest Genie 2010
Paspalum spp. (paspalum)	cucurbits	Pest Genie 2010
Paspalum urvillei (giant paspalum)	cucurbits	Pest Genie 2010
Pennisetum clandestinum (kikuyu grass)	cucurbits	Pest Genie 2010
Poaceae (all grasses)	sweet corn	Qld DAFF 2012
Sorghum halepense (Johnson grass)	cucurbits	Pest Genie 2010
Urochloa spp. (liverseed grass)	cucurbits	Pest Genie 2010

Table 4.3 Herbaceous weeds in Australian vegetable crops

Weed botanic and common name	Examples of vegetable crops impacted by weed	Literature source/s
Bifora testiculata (bifora)	cucurbits	Aftab et al. 2010
Ciclospermum leptophyllum (slender celery)	lettuce; celery; carrot; parsley	Qld DAFF 2010; Qld DAFF 2012
Daucus carota (Wild carrot)	cucurbits	Sindel et al. 2011
Vicia monantha (vetch)	peas; beans	Qld DAFF 2012

5. Current weed control approaches

5.1. Herbicides

Herbicide options for vegetable producers include products that control a broad range of species (generally used before crop planting or crop emergence), or products that control selected weeds (often used after crop emergence). Choice of pre-emergent or pre-plant herbicide depends on the weed species causing difficulty, the following crops and relevance of plant-back periods for the herbicide, and the types of herbicides used previously. Herbicide rotation is recommended where possible to avoid weed resistance to commonly used herbicides (Qld DAFF 2012; 2013). Generally, there are relatively few selective herbicides for the control of broadleaf weeds in vegetable crops, particularly after the crop has germinated or been transplanted. However, some examples of selective herbicides are noted here for cucurbit, lettuce and brassica production.

Herbicides registered for broadleaf weed management in cucurbit production (Sindel *et al.* 2011):

- Clomazone – post-plant pre-emergence control of certain broadleaf weeds as well as grasses.
- Dimethenamid-P – post-plant pre-emergence control of certain broadleaf weeds as well as grasses.

Herbicides registered for broadleaf weed management in lettuce production (Qld DAFF 2010; Crop Care 2013):

- Propyzamide – pre-emergence (post-seeding) or at-transplant; controls a range of broadleaf and grass weeds in lettuce crops, but is ineffective against some Asteraceae weeds such as common sowthistle.
- Pendimethalin – only in transplanted lettuce, and used before transplanting; also controls several broadleaf and grass weed species, including common sowthistle.
- Propachlor – pre-emergence (post-seeding) or at-transplant; effective control of potato weed compared to the other selective products.
- Dacthal – registered in November 2013 for pre-emergent control of weeds in transplanted lettuce crops.

No post-emergence broadleaf selective herbicides are available in lettuce crops (Qld DAFF 2010).

Herbicides registered for broadleaf weed management in brassica (broccoli, cauliflower and cabbage) production (Qld DAFF 2013):

- Oxyflourfen – pre-plant (4-7 days before planting transplanted brassicas). Controls a wide spectrum of important broadleaf weeds, but unlikely to control grass species.

- Metolachlor or S-metolachlor – spray immediately after planting. Controls potato weed, pigweed, some amaranthus and deadnettle, but not effective against fat hen, small-flowered mallow, or brassica weeds such as turnip weed or wild radish.
- Propachlor – similar mode of action to metolachlor, but less effective against thornapples and nightshades, and more effective against fat hen and mallows.
- Pendimethalin – applied before transplanting. It is effective against many broadleaf and grass weed species, especially fat hen and brassica weeds (when combined with propachlor).
- Chlorthal-dimethyl – often suppresses rather than controls broadleaf and grass weeds in direct-sown brassica crops.
- Trifluralin – mainly effective against grasses in direct-sown brassica crops, but does manage pigweed, amaranthus and knotweed.

In-crop selective herbicides for broadleaf weeds are not available in brassica crops, so that cultivation and hand-weeding are the only alternatives (see Sections 5.2 and 5.3) (Qld DAFF 2013).

Grass weeds are rarely a problem in cucurbit, lettuce and brassica production, as several post-emergence selective herbicide options are available, including fluazifop-p-butyl, sethoxydim, quizalofop and clethodim. However, not all grass weeds are managed by the available products, and farmers need to be aware of the potential for herbicide resistance. Farmers must also take into account withholding periods, which can be up to 63 days (in the case of quizalofop use within a cabbage crop) (Qld DAFF 2010; Sindel *et al.* 2011; Qld DAFF 2013).

5.1.1. Herbicide crop damage

The range of herbicides available for use within vegetable crops is restricted since vegetables are highly susceptible to damage from most residual herbicides (Lovatt 1995). In a trial of several potential pre-emergence herbicides for use in Australian cucurbit crops, Macleod *et al.* (2000) found that several were unsuitable due either to unacceptable crop damage or limited weed spectrum control. Even herbicides that are registered for use in cucurbits in Australia can damage the crop, although damage is often minor, within acceptable limits, or may be minimised by correct application (Henderson 2000; Macleod *et al.* 2000). Pendimethalin and propachlor can cause lettuce crop stunting in certain conditions at maximum application rates (Qld DAFF 2010). In brassica crops, a number of pre-plant or pre-emergence selective herbicide options are available, however these can cause damage to the crop under some circumstances. Oxyfluorfen, metolachlor and S-metolachlor can cause burning or stunting of crop seedlings, while pendimethalin can significantly damage brassica crops in waterlogged soils or very cold weather conditions (Qld DAFF 2013). Use of these chemicals may also result in long plant back periods for sensitive following crops – for example, there is a 6 month plant back period for onions when oxyfluorfen is used in a brassica crop, and 12 months for silver beet when pendimethalin is used in lettuce and brassicas (Qld DAFF 2010; HAL 2011).

5.1.2. Weed control success

In cucurbits, fluazifop-p, sethoxydim and quizafolop-p-ethyl are successful herbicides for controlling grass weeds in pumpkin and grammas, as well as in zucchini and squash. It is possible to spray these herbicides within the crop post-emergence to achieve control of grasses, but they have long withholding periods (Lovatt 1995; Murison 1995). Clomazone provides good pre-emergence control or suppression of various grasses as well as apple of Peru (*Nicandra physalodes*) and potato weed (*Galinsoga parviflora*) (Henderson 2000). It can be used to control a range of other broadleaf weeds but is ineffective against wild radish (*Raphanus raphanistrum*), amaranthus (*Amaranthus* spp.) and fumitory (*Fumaria* spp.) (Macleod *et al.* 2000).

In lettuce crops, the success of pre-emergent herbicide application depends on two factors (Qld DAFF 2010):

- Minimising the time between the final bed preparation cultivation (or knock-down herbicide application) and application of the pre-emergent herbicide. A longer delay (more than two or three days) is more likely to result in germination of new weeds that will not be controlled by the pre-emergent herbicide.
- Maintaining an effective 'herbicide blanket' requires minimal soil disturbance from any cultural operations within the crop beds after the herbicide has been applied, such as transplanting, hand weeding or in-crop cultivation weeding. The goal is to avoid stimulating further weed emergence.

5.2. Tillage/cultivation

Mechanical tillage or cultivation, in combination with herbicide use, is the most common form of pre-plant and early post-emergence weed management used on Australian vegetable farms (Henderson and Bishop 2000). Tillage is conducted at all stages of the crop in many cases. Options include pre-plant tillage during and after bed forming, in-crop cultivation before the crop canopy has closed to control early weed flushes ('intra-row'), and cultivation between the crop rows at various stages depending on the crop being grown ('inter-row') (Melander *et al.* 2005; Qld DAFF 2010; Sindel *et al.* 2011).

5.2.1. Weed control success and viability

Cultivation is often used not only to kill existing weeds, but to break seed dormancy and encourage germination of new weed cohorts which are then controlled with a knock-down herbicide or another cultivation before the crop is planted (Stall 2009; Qld DAFF 2010 – see also Section 5.12). The latter approach 'is relatively cheap and easy, leaves no chemical residues and incorporates organic matter (i.e. the weeds) into the soil' (Qld DAFF 2012).

In the case of many vegetable crops (and many significant weeds), shallow cultivation are the only options to manage weeds within the crop beds, due to a lack of selective post-emergence herbicides for broadleaf weeds. The only viable but still much more expensive alternative may be later hand weeding – see Section 5.3). Post-emergence *intra-row* cultivation is relatively cheap and can control weeds effectively. Nonetheless, timing is critical for cultivation to be effective. Too early, and the pre-emergence herbicide 'blanket' may be breached, giving new flushes of weeds time to establish in the crop beds before the crop canopy closes. Early cultivation may also uproot crop plants before they have had a chance to establish. Too late, and weeds may be too large to kill with a shallow cultivation. There may also be insufficient space to manage weeds between the crop rows if cultivation is delayed too long and the crop plants have started to grow too large (Henderson and Bishop 2000; Qld DAFF 2010; Qld DAFF 2013). Late attempts at *inter-row* weed control using cultivation may also damage crop roots that have established in the inter-row space (Henderson and Bishop 2000). Nonetheless, inter-row cultivation is a successful weed control strategy in most cases, and generally has no negative impact on the crop (Melander *et al.* 2005).

Equipment is available that allows organic and conventional vegetable farmers alike to remove weeds by cultivating the soil within the crop rows, until the crop has spread to cover the beds at which point weeds become less of an issue due to crop competition (see Section 5.10). One such implement is the 'Weedfix' intra-row cultivator that is able to remove many young weeds while protecting the recently emerged crop from damage (Neeson 2003). Henderson and Bishop (2000) note that a number of such implements were available overseas, but at that time had been rarely used inside Australia. Nonetheless, this device is now available for sale in Australia[1]. Other options include spring-tine, drag or chain harrows, torsion weeders, finger weeders, and vertical brush weeders (Wardlaw 2004; Melander *et al.* 2005). These tools require considerable accuracy to avoid crop damage, but do facilitate significant weed population reductions without the need for herbicides (Wardlaw 2004).

Intra-row cultivation of this nature requires high precision and appropriate timing to minimise crop damage and maximise weed control. It must also be carried out when the crop is more established and is able to cope with some impact from the weeding equipment. Soil conditions at the time of weeding are important. Soil that is too wet may clog the cultivation equipment and allow weeds to re-strike. Cultivating when soil is too dry may lead to erosion in windy conditions, while weeds can be more difficult to remove from dry soil (Henderson and Bishop 2000; Wardlaw 2004). The optimum timing for intra-row cultivation to achieve the highest level of success also depends on environmental conditions, weed species present, and crop cultivar. Early control of weeds that are most likely to break through the crop canopy is the focus of weed control activity in tall leafy brassica crops such as broccoli and cauliflower. Slower maturing brassica crops that are less capable of out-competing weeds, such as some cabbage varieties, may require ongoing attention such as via hand-weeding later in the cropping period (Qld DAFF 2013).

Some disadvantages of intra-row cultivation include poor seedbed preparation, slow work rates due to the precision required, damage to soil structure where repeated use occurs, and delays during wet conditions which may mean that

[1] http://www.fixengineering.com.au/pr_weedfix.htm, accessed 27/5/14.

weeds are too large to control when conditions become suitable (Wardlaw 2004; Melander *et al.* 2005).

Intra- and, to a lesser extent, inter-row cultivation should only be deep enough to control weeds effectively. In some crops such as cucurbits, shallow cultivation may be up to 8cm deep, whereas for shallow rooted vegetable crops such as lettuce, approximately 3cm is sufficient. Deeper cultivation can break or damage crop plant roots, and impact negatively on crop nutrient and water uptake (Sanders 2001; Burt 2005; Stall 2009; Vic DEPI 2013). Deeper cultivation may also bring more weed seeds to the surface, and disturb soils treated with a residual herbicide. For crops with runner vines (such as cucurbits), inter-row cultivation generally ceases once the crop vines have started to run (Burt 2005; Stall 2009). The accuracy and efficiency of cultivation, and the potential for cultivating much nearer to crop plants, has been improved significantly by the advent of GPS technology in recent years (Melander *et al.* 2005; see also Section 5.8).

An important drawback of all forms of cultivation is that it contributes to soil compaction, surface sealing, poor water, air and nutrient movement into the soil, and erosion, by damaging the soil structure. Most farmers use cultivation extensively in their vegetable production system. However because of the soil health impacts, some farmers may prefer to adopt minimum tillage strategies instead, for example relying on herbicide control (Pattison *et al.* 2010; Qld DAFF 2012; see also Section 5.8.2).

5.3. Hand weeding

Hand weeding (or 'chipping') involves people walking through the crop controlling weeds, either by pulling them out by hand or digging them out with a conventional hoe. In many vegetable crops, hand weeding is the only feasible way to manage weeds within the crop rows at later stages of the crop given the lack of selective herbicide options, particularly for broadleaf weeds. The method is very successful for weed control, particularly for targeting troublesome individual weeds. Timing is critical for cost-effective hand weeding. For example, in a vegetable crop where the canopy shades the crop rows completely, the best results are achieved around 7-10 days before canopy closure (Henderson and Bishop 2000; Qld DAFF 2012).

Even in crops where late emerging weeds will not impact on yield greatly (such as lettuce and brassicas), selective hand weeding still makes economic sense. Not only can tall weeds such as potato weed, fat hen and mallow interfere with harvesting operations, but where weeds are allowed to set seed before harvest, they can cause problems in future crops (Qld DAFF 2010; 2013).

5.3.1. Cost

Hand weeding is an expensive option given the labour intensity required, and is most likely to be feasible in high value vegetable crops (Henderson and Bishop 2000). Recent research suggests that the labour costs for vegetable farmers have grown significantly, and that labour is by far the greatest input cost on a vegetable farm (Valle *et al.* 2014). For many farms, weed control would make up a significant portion of total labour cost, and hand weeding will be a large portion of this cost where it is used.

This financial burden will be particularly significant where other weed control methods have not been successful, or where selective herbicide options within the crop rows are not available. In an organic onion crop for example, a high weed burden can result in time spent of approximately 600 hours per hectare in weed control, whereas transplanting the crop into a field following careful cultivation can reduce this burden to between 10 and 50 hours per hectare (Melander *et al.* 2005). These weeding times will be significantly less in conventional production systems when herbicides are available to reduce the weed burden within crop rows (see Section 5.1).

The growing cost of hand weeding makes it increasingly impractical for vegetable producers as a tactic to rely heavily on. Instead, hand weeding should be combined with other weed management techniques that are able to reduce the weed burden at the later crop stages where hand weeding might normally be considered. A particularly important role for hand weeding will be to control new colonies of weeds, and 'mop up' residual populations after other control activity has taken place (Henderson and Bishop 2000).

5.4. Plastic mulch film

Polyethylene plastic mulch is 'the mainstay of weed control in several high value fruiting vegetable industries in Australia' (Henderson and Bishop 2000). Plastic mulch has been available for vegetable production since the 1950s, and revolutionised the production of several vegetable crops (Lament 1993). Plastic mulch is an expensive weed control option, although it is feasible in high value crops such as capsicums, tomatoes, melons and other cucurbits. It delivers a number of other benefits to the crop, including soil moisture retention, water savings, warming the soil, enhance crop yield and quality, delivering earlier-maturing crops, controlling disease, managing aphids (in the case of reflective mulch films), and preventing the crop fruit from resting directly on the soil (Lament 1993; Henderson and Bishop 2000; Heisswolf and Wright 2010; Qld DAFF 2012). In Australia, black film is used in the cooler months or regions, and white film in the warmer months or regions, to regulate soil temperature (Henderson and Bishop 2000). Although plastic mulch has been in widespread use in northern Australia for some time, water scarcity has resulted in increased adoption in southern Australia (Heisswolf and Wright 2010).

Plastic mulch controls weeds by restricting the amount of light available for seed germination. Fumigation is often used before planting to increase the effectiveness of black plastic as a pest and disease control agent. Fumigation is also an effective method of controlling weeds, and is more likely to be needed where clear plastic mulch films are in use (Lament 1993; Henderson and Bishop 2000; see also Section 5.9).

It is possible for some weeds (such as nutgrass, *Cyperus rotundus*) to survive under the plastic long enough to pierce the film and establish in the crop rows (Lament 1993; Henderson and Bishop 2000; Sindel *et al.* 2011), while weeds may also grow through the planting holes in the plastic mulch where the crop is planted (NT Department of Resources 2012). Other methods of control such as hand weeding, spot-spraying using a selective herbicide, or reliance on crop competition are necessary in these circumstances. This includes spot spraying of grass weeds growing through the planting holes with a selective herbicide, while vegetable plants are still small. In plastic mulch systems, weed control will also still be necessary in inter-row and headland areas (Qld DAFF 2012; NT Department of Resources 2012).

5.4.1. Weed control success and viability

Plastic mulch is very effective at controlling weeds in the crop rows of high value crops such as cucurbits (Department of Resources 2012). Despite its high cost, it is considered by cucurbit farmers in Australia to be the most effective and economical form of weed control (Sindel *et al.* 2011), despite ongoing trials into alternative mulches such as living and killed systems, organic mulch and biodegradable paper and polymer-based films (Heisswolf and Wright 2010; see also Sections 5.6, 5.8, and 6.3). Olsen (2000) found plastic mulch to be not only the most cost-effective form of 'transported mulch' on a per hectare basis (Table 5.1), but as effective in terms of crop yield as the biodegradable mulch films tested, and more effective for crop yield and weed control than transported organic mulch options, and killed *in-situ* organic mulch.

Table 5.1 'Transported mulch' costs per hectare (Olsen 2000)

Transported mulch type	Cost ($/Ha)
Plastic mulch (polyethylene)	$860
Recycled newspaper	$1,300
Sawdust	$1,600
Gromulch paper film	$1,630
Sorghum hay	$2,000
Mater-Bi biodegradable polymer	$3,300
Hessian	$4,000
Sugarcane trash	$5,900
Composted mulch	$9,300

Nonetheless, some mitigating factors call into question the longer term viability of plastic mulch for cucurbit production. Plastic mulch is difficult and expensive to recycle. The cost of removing it from the paddock and disposing of it in Australia were between $150 and $249 per hectare in 2000, a similar cost to that in the United States (Olsen 2000; Olsen and Gounder 2001).

Perhaps the most significant mitigating factor, however, has been growing concern over the environmental impact of used plastic mulch disposal (Heisswolf and Wright 2010; Sindel *et al.* 2011). This factor alone may make plastic mulch use untenable in the longer term. This issue is discussed in more detail in Section 6.1.4. Biodegradable mulch film alternatives are also available, and are discussed in Section 6.3.

5.5. Crop rotation

Crop rotation is commonly used in Australia to give farmers the opportunity to control pests and diseases that impact on vegetable crops, such as fusarium which may be controlled by several years of growing other crops in the infected paddock, accompanied by fumigation (Dimsey 1995; Coleman 2003). In addition to having a useful role in non-chemical crop management, other benefits of crop rotation (Henderson and Bishop 2000; Watt 2009; Blaesing 2013) include:

- maintaining species diversity and soil biodiversity (and therefore soil health),
- achieve good soil structure, high organic matter and water holding capacity,
- increase soil carbon content,
- reduce the need for nitrogen fertiliser inputs, where nitrogen-fixing rotation crops are used,
- optimising the use of resources (land, equipment and capital) outside the vegetable production season or in response to commodity prices, and
- diversifying the farmer's production base.

5.5.1. Weed control success and viability

The weed control benefits of rotations are often of secondary importance to many farmers (Henderson and Bishop 2000). Nonetheless, rotation is a useful weed management tool for controlling many broadleaf species on a farm where vegetables are grown. Crops of the same family grouping should not be grown continuously in the one area or paddock to maintain soil health and minimise disease build-up. However, rotation between broadleaf and narrow leaf crops is particularly useful as broadleaf weeds may be selectively controlled, for example with selective herbicides, much more easily in the narrow leaf 'graminoid' rotation crop (Pattison *et al.* 2010; Qld DAFF 2012). By growing a rotation crop or variety of rotations, farmers have the opportunity to control species which are otherwise difficult to control within a vegetable crop (Masiunas 2008). In this respect, a knowledge of the weed spectrum across each paddock is essential to allow crop rotation planning (Wardlaw 2004).

On one farm in NSW (Watt 2009), crop rotations with wheat and other broadacre cereal crops made it possible to control paddy melon (*C. myriocarpus*) using selective herbicides and fumigation. These options were not available to control this weed when cucurbits were grown. This means the weed was less prevalent, and consequently easier to manage, in the following cucurbit crop. Some cover crops such as forage sorghum or brassicas may also be grown as a rotation crop with its own economic value, with many of the benefits discussed in Section 5.7 (Henderson and Bishop 2000; Qld DAFF 2012).

5.6. Transported organic mulch

Wright (2000) and Olsen and Gounder (2001) reviewed a number of transported organic mulches (organic material transported onto the farm) as possible substitutes for plastic in Australia. These included sawdust, sugarcane byproducts, composted vegetative mulch, forage sorghum hay, recycled newspaper and cardboard cartons, and hessian.

5.6.1. Weed control success and viability

Olsen and Gounder (2001) also found that weed control under hessian, sawdust and sugarcane trash mulches was relatively ineffective, to the extent that weeds in unweeded plots had an unacceptable negative impact on yield ('weight of marketable fruit') for the capsicum crops used in the trial. Wright (2000) discovered that recycled newspaper mulch also provided relatively poor weed control, although suggested the layer of paper used may have been too thin. For newspaper, recycled waxed fibre cardboard cartons, and bagasse (a by-product of sugarcane harvesting) trials, yield was impacted by weed competition in unweeded plots. The depth and cover of organic mulches is often insufficient to provide an effective barrier to weed development. Uneven weed suppression allows some weeds to grow through the mulch, although reasonable success may be achieved of the mulch is applied correctly (Kristiansen *et al.* 2008; Qld DAFF 2012).

Organic mulches offer farmers an opportunity to improve soil quality by adding large amounts of organic material to the soil, though it can tie up soil nitrogen, requiring additional fertiliser to be applied (Qld DAFF 2012). Table 5.1 above suggests that organic mulches are not viable alternatives for vegetable farmers on the basis of price alone (Wright 2000; see also Kristiansen *et al.* 2008). They are also and logistically difficult to transport to farms and to apply evenly over a large area of land. The vegetable industry lacks suitable machinery to apply organic mulches effectively, and organic material in crop beds may be associated with nutrient immobilisation, increased disease and pest activity, increased pesticide phytotoxicity, and allelopathic crop suppression (Henderson and Bishop 2000; Wright 2000; Olsen and Gounder 2001).

Relative ineffectiveness and high cost means that, in economic terms, transported organic mulches are an unrealistic alternative to polyethylene plastic mulches at this stage, particularly for large-scale farming enterprises (Olsen and Gounder 2001). Despite this, organic mulch may be a suitable alternative for smaller-scale producers who have ready access to a supply of mulch, or for organic producers who are keen to find an alternative to plastic mulch and/or selective herbicides.

5.7. Cover crop mulches

Cover crops, or 'green manure crops', are a commonly used approach to improve soil quality and structure outside the normal cropping season, and may be used to increase organic matter within a permanent or semi-permanent bed system (Rogers *et al.* 2002; Rogers 2007; see also Section 5.8.2). A number of grass, legume and biofumigant crops are available (Pattison *et al.* 2010; biofumigation is discussed further in Section 5.9.1). Dense green manure crops may also be planted to suppress weeds outside the normal cropping season, including weeds that host pests and diseases. Crop soils can suffer greatly in a relatively short space of time under constant cropping and tillage pressure, including greater risk of exposure to weed invasion, and so a green manure cover crop is important in improving the structure of the soil (NT Department of Resources 2012).

However, green manure cover crops also have the potential to act as a mulch substitute within a vegetable crop, and may be a substitute to in-crop herbicide application and/or tillage, or plastic mulch film (Rogers 2007). These 'cover crop mulches' are often referred to as living and killed mulch systems. They involve planting a cover crop in the crop rows before the crop is planted. It may be maintained as a living mulch if the cover crop is 'either dormant, or sufficiently retarded (e.g. by low rates of herbicide) so as not to significantly compete with vegetable crops'. Alternatively, a killed mulch may be created by killing the cover crop, for example by applying a non-selective herbicide, waiting for the cover crop to die and then rolling it flat, and planting vegetables into the stubble (Henderson and Bishop 2000; Wardlaw 2004; Rogers 2007). In either case, the cover crop mulch is intended to suppress weed growth until the vegetable crop has covered the beds, at which point weeds are unlikely to penetrate the crop surface. The crop is generally transplanted straight into these prepared beds, without the use of tillage (Rogers 2007). It is good practice to ensure good weed control prior to sowing the cover crop mulch, either through cultivation of the crop beds, or herbicide application (NT Department of Resources 2012). The approach requires more irrigation water than other mulch options (Qld DAFF 2012).

5.7.1. Weed control success and viability

Living and killed mulches have been found to control weeds within crops with some success, suppressing weed populations to the extent that they do not compete with the crop. A variety of cover crop species are available, many of which are *Brassica* or *Trifolium* spp. Many of these have been rated as providing good to excellent weed control, although it remains vital to control weeds within cover crops to prevent seed production, and to reduce the weed seed bed over time (Rogers *et al.* 2002). In this respect, there is a place for herbicide use in combination with a killed mulch cover crop (Rogers 2007). The effectiveness of cereal crops such as wheat and ryecorn as cover crops may be due to their allelopathic effects in preventing weed germination (HAL 2005; see also Section 5.9.1). Experiments have shown that a rye corn cover crop significantly reduced weed growth in a broccoli crop, to the extent that no other forms of weed management were required (Wardlaw 2004). However, such systems (particularly living mulches) can be difficult for farmers to implement, as a balance needs to be struck between suppressing weeds and ensuring the crop establishes successfully through the mulch (Henderson 1998).

Henderson and Bishop (2000) summarise a number of overseas and Australian studies of killed mulch systems used in tomatoes, lettuce, brassicas, and broccoli. Yield losses compared to using plastic mulch are minimal, although some modifications to planting equipment and crop management may be required (Henderson and Bishop 2000; HAL 2005). Living mulches can reduce weed populations to non-competitive levels, and improve the condition of the soil. However they may provide insufficient weed control, or shift the weed spectrum to biennial or perennial weeds. Living mulches may also compete with the crop for nutrients, although competition may be managed by killing the mulch in a narrow strip along the planted row (Henderson 1998).

Table 5.2 The proposed advantages and disadvantages/problems of living and killed mulch systems (excerpt from Henderson and Bishop 2000)

Advantages

- being more environmentally acceptable than standard plastic film systems;
- improved soil structure and biological activity, achieved through extended periods of vegetative ground cover, increased organic matter cycling and faunal activity;
- improved nutrient cycling and/or generation by using deep-rooted or nitrogen-fixing cover crops, plants that host mycorrhiza, and incorporation of inorganic nutrients into organic pools;
- allelopathic impacts on weeds (cereal rye is an often quoted example);
- acting as reserves for beneficial fauna (predators or parasites of pest species), and providing more crop-friendly microclimates;
- reduced potential for wind and water erosion; and
- reduced wind and soil contact damage to crops, e.g. rockmelons and watermelons (plant mulches give tendrils from these crops an anchor point to resist foliage displacement by wind).

Disadvantages/Problems

- adverse impacts on vegetable crops (allelopathy, nutrient immobilisation, increased pest or disease activity and colder soil temperatures);
- increased expense for ground preparation and planting through the cover crop, as well as the opportunity costs of tying up resources in the mulch that could otherwise be used for cash cropping;
- insufficient mulch present to give effective weed control, or evolution of weed spectrums able to establish under mulch/minimum tillage conditions (common sowthistle seems to be a weed favoured by these circumstances);
- binding of many soil-applied herbicides to the organic matter; and
- the requirement for advanced management skills to implement killed- and living-mulch systems.

Cover crop organic mulch systems are in limited use in Australia (Henderson and Bishop 2000), though the viability of this approach, and best practice techniques for its implementation, are likely to be refined given longer-term questions over the sustainability of plastic mulch. Research in the United States suggests that cover crops can be used effectively in conjunction with pre- and post-emergence herbicides to suppress broadleaf weed growth and result in higher vegetable yields (Walters and Young 2010).

Where living and killed mulches are used in Australia, they are generally implemented in a permanent or semi-permanent bed with semi-permanent drip irrigation systems. The cover crop is grown over summer and controlled with a mixture of slashing and knock-down herbicide application (Wright pers. comm.).

Experimental work funded by HAL (Rogers 2001) on a number of trial sites in Australia led to a best practice manual being developed for no-till permanent beds in horticultural production. Weeds within the various cover crops were controlled successfully by several herbicides including Fusilade® (fluizafop-p butyl) to control grass weeds in Centro stands, Kamba® (MCPA) to control broadleaf weeds in grass cover crops, and Jaguar® (hydroxybenzonitrile + nicotinanilide) to control some broadleaf weeds in legume cover crops. This manual suggests that cover crops may be killed prior to planting either with herbicide, or mechanically with a crimping roller or flail mulcher. Pre-emergent herbicides may be used to control weeds in a cover crop system, although their effectiveness is reduced by the organic mulch layer, while herbicide damage may occur in the crop once it emerges.

The cost of establishing a killed mulch is approximately a quarter of the cost of plastic mulch (including plastic mulch disposal costs). Killed mulches also have the potential to improve soil health. Currently, however, many commercial farmers do not consider killed mulches a viable alternative. This is because killed mulches lead to uneven crop growth, lower yield, long establishment time, possible build-up of soil pathogens, emergence of volunteer weeds from the cover crop, and poorer weed control than plastic mulch (Olsen 2000).

As with transported organic mulches, cover crop mulch systems are therefore not as effective as plastic for weed control, although the logistics and costs are less of an issue than they are for transported organic mulches. However, the longer-term viability of these systems is still dependent on further research that may refine their ability to control weeds more effectively. Their viability may also depend on the comparative longer-term viability of plastic or biodegradable polymer films. Research is also required to overcome poor soil contact with the root ball of the crop during planting, and to address nutrient tie-up and allelopathy impacts on the crop (Olsen 2000).

5.8. Precision agriculture

5.8.1. Controlled traffic

Controlled traffic farming (CTF) is an effective way to reduce soil compaction in cropping and horticulture situations. CTF involves establishing permanent wheel tracks outside of the crop growing area and in between crop rows (using Global Positioning Systems and related technology), along which all wheeled farming equipment operates. Research suggests that in a conventional potato paddock, traffic is normally 300%; that is, every square metre is driven on three times during a production cycle. Under a CTF regime, traffic reduces to around 30% of the paddock (Hincksman 2013). When combined with planned efficiencies in farm layout, CTF delivers a range of management benefits to farmers using raised growing beds (such as vegetable farmers) including fuel savings, improved and more consistent soil structure and health across the paddock, improved soil moisture retention, and higher yield (McNeill *et al.* n.d.; Williams 2007; Brennan 2010; Tasmanian DPIPWE 2010). CTF is increasingly being adopted by European organic vegetable farmers in recent years given the improving accuracy of guidance technology. Many European farmers have implemented a seasonal CTF system (SCTF) in which all pre-harvest equipment tracks are maintained, while harvest traffic is random (Brennan 2010).

CTF gives vegetable farmers greater scope to operate an effective permanent bed zero till system which is not subjected to soil compaction (Hincksman 2013). One of the benefits of zero till systems is reduced weed seed stimulation, and therefore less weed competition in the beds (McNeill *et al.* n.d.; Tasmanian DPIPWE 2010). Controlled traffic and permanent beds can be integrated with cover crop organic mulches and strategic use of pre- and post-emergent herbicides to control weeds in the early crop stages. One large enterprise in North Qld has successfully grown around 40-50ha of zucchini annually for some years using this integrated system (Wright pers. comm.). Australia is a world leader in CTF in dry-land grain and sugar farming, and it is well established in Queensland, NSW and Victoria in broadacre production. CTF application to vegetable production is most advanced in Tasmania, where trial work has demonstrated the considerable production and environmental benefits (Brennan 2010; Hincksman 2013). Nonetheless, CTF does have shortcomings in the vegetable industry. These include the initial cost of satellite guidance systems, and major design changes required for harvesting equipment to implement a 'season-to-season CTF system' (Brennan 2010; Hincksman 2013).

5.8.2. Reduced till permanent or semi-permanent beds

Reduced- or no-till permanent or semi-permanent crop beds, with a semi-permanent drip irrigation system, are becoming popular (often in combination with an organic cover crop mulch – see Section 5.5; and controlled traffic – see Section 5.8.1). They provide an alternative to heavily cultivated soil to restrict weeds and maintain soil moisture under drip irrigation. They can be readily integrated with a CTF system. Reduced tillage may involve fewer cultivation passes prior to seeding, while zero tillage involves leaving the crop stubble in place, and using knife-point or disc seeding (WANTFA 2011). The concept of no-till permanent beds may be becoming more acceptable to farmers due to the availability of no-till planters, effective techniques for producing and managing cover crop mulches, and improvements in integrated weed management (see Section 5.14). Suitable in-crop and inter-row pre-emergent and non-residual post-emergent herbicides may be used strategically to control weeds during the vegetable growing season – though there is concern that a permanent or semi-permanent bed system actually increases the farmer's dependence on herbicides (Rainbow 2005). There is a trend in Northern Queensland to move towards this type of production system, one that is expected to continue if a wider range of non-residual herbicides become available to farmers (Wright pers. comm.). A best practice manual for permanent beds using killed mulch cover crops has been produced by HAL (Rogers 2001). Reduced tillage and soil disturbance gives soils a greater chance of being healthy, with associated benefits for the crop (Pattison *et al.* 2010). However, there are potential drawbacks including greater reliance on knock-down herbicides such as glyphosate, and a farm management system which selects for annual grass weeds (Sindel 2000).

5.9. Fumigation and biofumigation

Fumigating the soil in the formed crop beds using broad spectrum chemicals such as methyl bromide and metham-sodium has been a common practice amongst Australian vegetable producers, largely for its benefits for managing nematodes, diseases, and insect pests. However, fumigation may have secondary weed control benefits, and render herbicide use unnecessary in some circumstances (Dimsey 1995; Henderson and Bishop 2000; Ullio 2004; Qld DAFF 2010). Fumigation at least two weeks before crop planting allows the fumigant to dissipate in the soil effectively. Fumigation with metham, in combination with the herbicide halosulfuron controlled a number of species under plastic mulch in a US study, including yellow nutsedge (*Cyperus esculentus*), without having a negative impact on watermelon yield (Johnson and Mullinix 2002). The precise effects of fumigation on weeds are not widely understood amongst farmers (Henderson and Bishop 2000), and its impact does not appear to have been explored in detail in Australia. Nonetheless, fumigation does appear to be effective in controlling difficult weeds in Australia such as nutgrass (Ullio 2004).

Chemical fumigation faces an uncertain future due to environmental and social concerns (see Section 6.1.5).

5.9.1. Biofumigation using killed mulches

This uncertain future has led to research into 'biofumigation', using cover crop mulches to deliver soil fumigation. Some brassicaceae plants such as canola and mustard release fumigant-like compounds into the soil as they decompose. Where brassica plants are used as a killed mulch, this process is thought to have some positive impact on insects and diseases within vegetable crops, and may have some benefits for weed control as well – both by managing weeds in the crop, and by reducing the seed bank (Henderson and Bishop 2000; Melander *et al.* 2005; Lefebvre *et al.* 2014).

A number of brassica varieties have been developed in Australia for biofumigation and suppression of weeds in horticultural crops, including BQ mulch, Rangi rape, Brassicas napus, Fumus, and Mustards (Pattison *et al.* 2010). Fumigator sorghum also adds a higher quantity of dry matter to the soil than many other cover crop mulch options, in addition to its biofumigation potential (Ramirez 2012). Some biofumigant crop options were evaluated by Kristiansen *et al.* (2005) for their ability to control weeds pre-crop (as a living mulch) and in the lettuce crop (as a killed mulch incorporated into the soil) during the growing season. After ten weeks growth, the brassica cover crops were cultivated into the soil. The study found that brassica cover crops were effective at suppressing weeds in the pre-crop phase as a living mulch, but that weed control effectiveness within the crop as a killed mulch was not significant. Similarly, Macleod *et al.* (2000) trialled two brassica biofumigant mulches (BQ Mulch and Weedcheck), which were incorporated into the soil prior to crop sowing. They also found that weed control was not acceptable within the crop.

Mustard biofumigant cover crops have been trialled in the United States for their potential to allow pumpkin and cucumber farmers to shift to post-emergence herbicide use and ensure that weed resistant biotypes do not develop. The research found that some crop damage resulted from use of a mustard biofumigant crop, while the effectiveness of the method depended on weed species, timing, and the mustard cultivar. Ongoing work seeks to refine the use of mustard biofumigants and overcome some of these limitations (Masiunas and Anderson 2009).

5.10. Crop competition

Crop competition means ensuring that good crop cover is established quickly to give the crop a competitive advantage over weeds. This includes sufficient plant density to allow the crop to form a dense canopy, making it difficult for weed seeds to germinate for lack of light. Weeds are not a significant problem once the crop canopy closes fully (Masiunas 2008), however this is only an option for vegetable crops where the plants are capable of forming a closed canopy (Qld DAFF 2012). Factors taken into account include soil condition and fertility (including fertiliser application), choice of crop variety, ensuring good water control (irrigation and drainage), sowing or planting adequate plant populations, and planting times (Rogers *et al.* 2006; Qld DAFF 2012).

Another option to consider for some vegetable crop varieties is to transplant seedlings into the field rather than growing in the field from seed ('direct-sown' crops). This allows the crop to establish more quickly, and gives it a better chance of out-competing weed species before they have a chance to establish in great numbers (see for example Rogers *et al.* 2006). In some vegetable crops such as brassicas (e.g. broccoli, cauliflower and cabbage), the spectrum of weeds that may be controlled by available herbicides is more limited in direct-sown crops than transplanted crops. Weeds that emerge at the same time as a direct-sown brassica crop are also more difficult to control using cultivation than they are in a transplanted crop, as the root system anchorage of the crop and weeds is similar (Qld DAFF 2013).

Trials in the United States have shown that if broadleaf weeds (such as smooth pigweed - *Amaranthus hybridus*) emerge 4-5 weeks after a watermelon crop, they have little or no impact on yield (Stall 2009). Research in Australia has found that native vegetation may be used in non-crop areas of the farm (next to traffic areas and waterways, along fencelines and so on) to out-compete weeds in these areas of the farm that harbour pests and diseases potentially damaging to the crop. Native plants in these areas have been found to harbour less pests, while also hosting higher numbers of beneficial insects (Powell 2006; Acton 2008). Effective pest and disease management is an important consideration in maintaining a vigorous crop (Qld DAFF 2012).

Trials in grains in Western Australia suggest that crop rows oriented on an east-west axis (at right angles to the sunlight direction) may suppress weed growth in the inter-row space through more effective shading (Borger *et al.* 2010).

5.11. Farm hygiene

Farm hygiene practices limit the spread of weed seeds and propagules (as well as pests and diseases) across and between properties, and onto crop beds from other parts of a property where weeds are present. Diligent farm hygiene can be used to successfully limit the spread of weeds, while poor hygiene practices can allow weed infestations to take hold on farms that were previously relatively weed free (Sindel *et al.* 2011). Farm hygiene appears to be an important approach to reduce the risk of weed spread (Sindel *et al.* 2011). Hygiene practices available to farmers that may help to limit the spread of weeds (Henderson and Bishop 2000; Grundy 2007; Watt 2009; Qld DAFF 2010; Sindel *et al.* 2011; Qld DAFF 2012) include:

- Establishing permanent or set vehicle tracks and laneways to restrict the amount of soil spread by machinery onto cropped areas of the farm (controlled traffic; see Section 5.8.1).
- Restricting weed growth along these and other traffic and drainage areas on the farm, including by controlling weeds in these areas before they have set seed, or by maintaining ground cover with suitable grass species (e.g. Kikuyu) to limit the ability of weeds to establish.
- Careful management of uncropped areas on the farm, such as field fringes, headlands, fallow fields, or around buildings.
- Washing down or disinfecting all cultivation and harvesting equipment, including bins and pallets (particularly when using contractors) before bringing it onto the property or transferring it from one part of the property to another.
- Restricting movement of machinery and people onto the property as much as possible, and establishing a single delivery point near the property entrance.
- Buying certified seed and seedlings, and being aware of potential weed spread if transported organic mulch is used.
- Planting vegetable crops in paddocks which have a good history of weed control. For example, Qld DAFF (2010) recommend growing lettuce in paddocks that have at least two years of good weed control, achieved by selective crop rotation and cover cropping. Otherwise, farmers may face a large seedbank, making it difficult to grow lettuce.

5.12. Stale and false seedbeds

A stale seedbed involves preparing the seedbed for planting and then leaving it for between several days and several weeks before planting. During this fallow period, weeds are allowed to germinate, and may even be stimulated through pre-irrigation. Before crop planting, the weeds are controlled with a knock-down herbicide such as glyphosate, paraquat or diquat. Stale seedbeds are a beneficial weed control technique as soil disturbance before crop planting is limited, so that buried seeds are less likely to germinate (Lonsbary *et al.* 2003; Taylor 2009; Qld DAFF 2010). In organic production systems, thermal approaches such as flame or steam application may be used to control the weed flush, in place of knock-down herbicides and to avoid further soil disturbance (Qld DAFF 2010; 2013; see also Section 5.13).

A false seedbed is similar to a stale seedbed, although weed control prior to planting is achieved by repeated shallow cultivations and knock-down herbicide applications, designed to encourage germination and/or control recently germinated weeds. Deep cultivations are not recommended, as they cause more weeds to germinate in the crop (Qld DAFF 2010; 2013). The goal of the false seedbed approach is to break down the weed seedbank in the top layer of soil, so that fewer weeds emerge during the crop growing season (Taylor 2009). False seedbeds raked before planting to control weeds and break up soil compaction also appear to improve crop germination and establishment in comparison with cover crop mulch systems such as wheat, possibly due to improved seed/soil contact (Sherriff *et al.* 1999).

5.12.1. Weed control success

Stale and false seedbed techniques appear to control weeds more effectively, and contribute to higher crop yield in cucumbers, than crop beds managed by conventional cultivation practices alone (Johnson and Mullinix 1998; Lonsbary *et al.* 2003). Lonsbary *et al.* (2003) explored the efficacy of stale seedbeds prepared at different lengths of time before crop planting. They found that the optimal seedbed was prepared 20 to 30 days before planting, using a knock-down herbicide (glyphosate) to control the weeds pre-plant. Johnson and Mullinix (1998) showed that repeated shallow tillage of a false seedbed reduced the number of weed seeds and weed diversity within a seedbed, partially replacing the use of post-emergence herbicides. False seedbeds also resulted in greater cucumber yield than beds treated pre-plant with glyphosate. In both cases, minimal soil disturbance during planting is also desirable to minimise weed germination during the early crop stages, reducing the farmer's reliance on post-emergence herbicide treatments (Johnson and Mullinix 1998; Taylor 2009).

Stale seedbeds can also be established using plastic mulch to control weeds (Wright pers. comm.):

> *A modified 'stale seedbed' technique is often employed where plastic mulch and drip irrigation is used. The beds are irrigated following plastic mulch being laid out and the crop is planted around 3-4 weeks later. This allows time for weeds to germinate and die due to a lack of sunlight (except for nutgrass which easily penetrates the mulch). The crop can then be planted by either direct seeding or using container grown transplants. This method greatly reduces weed growth around the hole in the mulch through which the plant/seed is planted.*

Stale seedbed techniques are of particular relevance to organic vegetable farmers, most of whom rely heavily on cultivation for pre-plant and early post-plant weed control. It is possible for organic producers to control weed germinations in a stale seedbed using thermal control (flaming or steam weed control – see Sections 5.13.1 and 5.13.2), achieving a good weed control with minimal soil disturbance, and decreasing subsequent weed emergence (Taylor 2009). Sindel *et al.* (2011) found that Australian cucurbit farmers rated stale and false seedbeds highly both for their affordability and effectiveness in managing weeds, but that there was a relatively low uptake of the approach. Low uptake may be due to the intensive nature of vegetable production in many parts of Australia. Where farmers are planting and harvesting crops year round, there may not be sufficient time and/or incentive to establish a stale or false seedbed.

5.13. Thermal weed control

Thermal weed control methods are particularly useful in low-till and permanent bed systems, and in organic systems where herbicides are not available to the farmer. While the initial outlay for thermal weeding equipment is higher than for tillage equipment, it can be between 50% and 80% cheaper than hand-weeding, and viable for relatively small farms of 6-20 hectares (Kristiansen and Smithson 2008). Research also suggests that effective intra-row weed control may be achieved in some cases by combining thermal approaches with intra-row cultivation (Melander *et al.* 2005).

5.13.1. Flaming

Flaming involves the use of natural gas- or propane-fuelled burners to expose weeds to ‘sufficient heat to disrupt cell membranes, destroying leaf and meristematic tissues’ (Henderson and Bishop 2000). The technique is commonly used pre-plant or early post-plant as a replacement for knock-down herbicides, and is therefore of particular interest to organic farmers. Flaming is generally more successful against broadleaf weeds with growing points above the ground than it is against grasses, where the growing point (meristem) is often either below the surface or concealed within new leaves (Henderson and Bishop 2000; Kristiansen and Smithson 2008; Mutch *et al.* 2008). Its other advantages are that it leaves no chemical residue, and does not result in soil disturbance (Melander *et al.* 2005).

However, flaming has other limitations in addition to its relative ineffectiveness against grass species. Optimal control often requires a number of flame applications, while smaller crop plants are generally more susceptible to damage from flaming than larger plants, so optimal control of weeds is achieved when the weeds are smaller than the crop plants (Mutch *et al.* 2008). It can also consume significant quantities of costly fossil fuels (Melander *et al.* 2005). Nonetheless, flaming has been recommended in Australia for organic farmers as an option for pre-plant weed control, once rainfall or pre-irrigation has allowed weeds to germinate in the beds (Neeson 2003).

5.13.2. Steam

The advantages of steam weeding over flaming include better heat transfer and reduced fire hazard risk. A comparative trial of steam weeding in Australia found that weed control was equivalent to manual techniques such as tillage and chipping, and to glyphosate (Kristiansen and Smithson 2008). Steam weeding may also be an option for spot control of weeds after crop planting in a killed mulch system (Diver 2002). The effectiveness of steam weeders can be enhanced by incorporating compounds such as CaO or KOH, which boost soil heating further through exothermic reaction with the steam (Melander *et al.* 2005).

As with flaming, however, steam weeding is of limited effectiveness in controlling grass weed species. Kristiansen and Smithson (2008) found that steam weeding equipment reduced broadleaf weeds by around 50% to 60%, whereas its control of grass weeds was much less effective. However the authors suggest that thermal methods *can* be used to control grass weeds, requiring application when the grass weeds are very young, and slower application speeds to improve the effectiveness of the steam or other thermal control technique. As with flaming, steam weeding consumes significant quantities of fossil fuels, and low work rates are also a problem with thermal approaches (Melander *et al*. 2005).

Nonetheless, it may be possible for farmers to use selective herbicides to control grass weeds in the crop, and use steam spot-control equipment to control broadleaf weeds before the crop canopy closes.

5.13.3. Soil solarization

Research outside Australia suggests that clear plastic may also be effective at controlling weeds and pests through ‘soil solarization’, a process that involves trapping solar radiation in moist soil (thermal weed control) for several weeks as an alternative to the non-transparent plastic/fumigation strategy. Soil solarization was explored in more detail in the US as a result of methyl bromide fumigation being phased out of use (Stapleton *et al.* 2005). Similarly, the technique has been explored in more detail in Italy due to the phasing out of a number of chemical weed control options (Candido *et al.* 2011). Both studies found soil solarisation to be effective in managing weeds within crop rows, and therefore to be a potentially viable option for organic and small scale farmers. Candido *et al.* (2011) found that crop yield (lettuce) was significantly higher in solarized plots than in non-solarized plots. However, Henderson and Bishop (2000) consider soil solarization to be uneconomic in Australia, given that the planting areas must be under clear film for anywhere between four and eight weeks for the solarization process to occur effectively.

5.14. Integrated weed management in Australian vegetable crops

In this chapter we have discussed the various weed control techniques currently available to Australian vegetable farmers. Most are particularly suitable at particular times during the season, or for particular management circumstances. However, it is rare for the techniques described in this chapter to be used in a vegetable crop in isolation: nearly all Australian farmers integrate a number of these techniques into a weed management strategy, because no single technique alone will effectively manage weeds in the crop during the entire growing season. For example, fumigation is commonly used in conjunction with plastic mulch and drip irrigation, cover crop organic mulches may be incorporated into a permanent bed system with controlled traffic and use of pre-emergent or selective post-emergent herbicides, and pre-plant cultivation is commonly followed by knock-down herbicide application to encourage weed germination and allow effective weed control before the crop is planted.

Integrated weed management (IWM) has been defined as 'a sustainable management system that combines all appropriate weed control options' (Sindel 2000). These options may be categorised as 'preventive methods' (reducing weed emergence in crop beds before crop establishment), 'direct physical methods' (used directly in the crop after sowing or transplanting), and 'cultural methods' (enhancing crop competitive ability). Techniques from each of these categories should be implemented to achieve sufficient control of weeds (Melander *et al.* 2005). IWM seeks to minimise the possibility of weed control failure, to reduce the impact of weed management activities on the environment (notably by minimising the farmer's reliance on herbicide use), and to ensure that the mix of techniques used will remain viable into the future (for example by reducing the risk of herbicide resistant weeds developing, or by accounting for the diminishing chemical weed control options available to farmers) (Sindel 2000; Newley and Treverrow 2006; Qld DAFF 2012; Charles 2013). IWM should also take into account the points along their life-cycle at which weeds are most vulnerable to the range of management options available, and to implement an appropriate control strategy accordingly (Henderson 1998). Persistence is important with respect to IWM. The effectiveness of an IWM strategy cannot be judged in a single cropping season, as it takes several years of effective management to reduce the soil seed bank (Blaesing 2013).

In vegetable production, the sustainability of 'quick fix' weed control techniques such as herbicide and fumigant use and plastic mulch is being questioned, and these commonly used techniques may become less viable in the future, or less acceptable to society (Henderson 1996). A more integrated approach is therefore desirable, however IWM is considered 'poorly developed' in Australian vegetable production, with a heavy reliance on herbicides and cultivation (Henderson 1996; McDougall 2007; Thompson 2011). The majority of vegetable farmers in Australia are currently using a 'Low or Basic IWM' approach. In addition to cultivation and pre- and post-emergent herbicides, this will generally include chipping and hand weeding in the crop rows, plastic mulch film where this is applicable, and possibly false or stale seedbed preparation of the crop rows (Sindel *et al.* 2011; Thompson 2011; RIRDC 2012).

The mix of techniques used as part of IWM in vegetable production will vary depending on circumstances and personal preferences. 'Medium or High IWM' will incorporate more detailed and intensive weed management (Thompson 2011). Some options may include various mulches and innovative cultivation techniques, weed mapping or surveying, crop rotations, farm hygiene, soil solarisation, precision weed control, and selective spraying (McDougall 2007; Thompson 2011; Blaesing 2013). These and other weed management techniques are discussed in Chapters 5 and 6. IWM is considered essential to the future of the industry (Sindel *et al.* 2011). However, many vegetable farmers currently using 'Low or Basic IWM' consider new approaches and technologies that may facilitate a more sustainable IWM to be most applicable to organic production (RIRDC 2012), and are therefore unlikely to consider adopting them in a conventional production system.

Henderson and Bishop (2000) presented a case study of successful IWM implemented by a Queensland celery and lettuce producer facing a heavy infestation of potato weed (*Galinsoga parviflora*). Many of these techniques were implemented for other reasons, or had other benefits, but nonetheless had a positive impact on weed control. The strategy included:

- Farm hygiene to restrict the ability of weeds to recolonize crop beds.
- Establishing cereal cover crops during 'non-cash crop periods' to not only build up the organic matter in the soil, but to allow selective control of broadleaf weeds with herbicide, and weed control with knock-down herbicide before the cover crop was planted.
- Using a drip irrigation system so that the non-irrigated inter-row space remained relatively dry and less likely to support weed growth.
- Growing crops (lettuce) with a short cropping period (transplant to harvest), so that weeds did not have time to establish properly in the crop rows.
- Habitually removing older weeds, especially those close to setting seed, once the bulk of the weed outbreak had been controlled.

The net result was to virtually eradicate potato weed on the property at little additional cost to the farmer. As Henderson and Bishop (2000) noted, '[a]ll that was required was a planned strategy to link the key management components in a sensible sequence, and the persistence to ensure that each step was diligently carried out'. However, IWM tends to be site-specific, and developing general guidelines is difficult.

5.14.1. The relationship of IWM to crop pest and disease management

IWM is an important part of a broader Integrated Pest Management (IPM) strategy within vegetable crops, in which all forms of pests are managed (Thompson 2011; AUSVEG 2012). Weed management both within and surrounding crops is required to reduce the impact of insect pests and diseases on the crop, as weeds often act as a host for important pests and diseases (see Section 3.3). McDougall (2007) lists current and possible IPM strategies for a variety of vegetable crops grown in Australia. In many cases, management of related or host weeds is recommended to reduce the impact of particular viruses, pests or diseases within the crop (McDougall 2007). Thompson (2011) proposed an 'IPM Continuum' for pest and disease management within vegetable crops, and considered weed management to be part of a 'Medium IPM' strategy, in which management of weeds that have the potential to host crop diseases and nematodes was undertaken. However, uptake of IPM amongst vegetable farmers appears to be fairly low, for a range of reasons relating to lack of expertise and knowledge, and belief that their current crop protection strategy is adequate (McDougall 2007; Blaesing 2013).

5.14.2. The relationship of IWM to soil health

While some innovative farming practices may address weed problems as well as plant/soil health problems (e.g. crop rotation), other practices may produce conflicting outcomes (e.g. reduced tillage may encourage soil borne diseases, while excessive tillage may damage soil structure; Pattison *et al.* 2010). Good weed control is important for soil health and management of significant soilborne vegetable pathogens, including *Rhizoctonia* sp., *Schlerotinia* sp., and *Verticillium* sp. (McMichael 2012). Weeds may be symptomatic of poor soil health, indicating an imbalance in the chemical, physical or biological health of the soil (Wardlaw 2004).

'Numerous research papers have reported how specific pathogens, and to a lesser extent pests or weeds, are suppressed or stimulated by certain measurable soil conditions. Different physical, chemical and biological soil condition indicators have been used in the various research projects' (Blaesing 2013). Techniques that improve soil health, such as cover crops (Section 5.7) may therefore be as important as cash crops due to their soil health and weed management benefits (Wardlaw 2004). Soil, water and nutrition management strategies should be incorporated into IWM to foster improved soil health. Similarly, it is hoped that the recently commenced HAL project, 'VG13076 - Soil condition management – Extension and capacity building', will extend to farmers the soil health benefits of effective weed management.

5.15. Organic weed management in Australian vegetable crops

Weed control is one of the most difficult tasks to achieve in vegetable production without herbicides. Weeds growing within the crop rows present the greatest challenge, especially in direct-sown small-seeded vegetables such as carrots. Severe crop losses can be incurred if weeds are not managed properly, however high labour costs generally result from the need to address this issue (Wardlaw 2004; Kristiansen *et al.* 2008; Ascard *et al.* 2011). A national survey of organic vegetable and herb farmers in Australia during the 1990s showed that most relied on hand weeding, slashing, mulch, and cultivation to control weeds (Kristiansen *et al.* 1999; 2007). Of the weed control techniques evaluated in this chapter, the following are relevant to organic vegetable producers:

- Hand weeding.
- Cultivation (primarily inter-row, but also including intra-row post-emergence cultivation).
- Transported and cover crop mulches.
- Controlled traffic, incorporating permanent or semi-permanent crop beds and possibly an organic mulch cover crop.
- Crop competition.

- Farm hygiene.
- Thermal weed control.
- False seedbeds (incorporating pre-irrigation to stimulate weed growth and control recently germinated weeds using shallow cultivation or thermal weed control).

Innovations in these methods are also of interest to conventional producers, as they may be incorporated into an IWM strategy for conventional vegetable production, and may also assist in addressing herbicide resistance and over-reliance on a limited range of herbicides. The European Weed Research Society has hosted several workshops on Physical and Cultural Weed Control, with workshop proceedings having been produced. This vast literature covers topics such as mechanical weed control, cultural weed control, allelopathy, mulches, cover crops, crop varieties, and thermal weed control[2]. Since the organic vegetable sector is unable to rely on herbicide to manage weeds, it provides a potentially useful source of innovation to benefit all farmers.

In some crop situations, plastic mulch film is used. Since organic producers are often (though not always) reluctant to use plastic mulch, organic mulch may be required not only for its moisture retention benefits but to 'provide a "clean" barrier between fruit and the bare soil, thus preventing staining of the underside of the [fruit]' (Neeson 2003). Some biodegradable mulch films (discussed in Section 6.3) may also be relevant to organic producers (Miao *et al.* 2013).

Of the methods available to organic producers, cultivation is possibly the most widely used form of weed control. With correct timing and approach, mechanical cultivation can remove 90% of weeds from a crop, while the remainder will need to be removed by other means such as hand weeding (Lanini 2009). Cultivation is considerably cheaper for organic vegetable producers than alternatives such as hand weeding or hay mulching, though results in lower crop yield (Kristiansen *et al.* 2008). Intra-row cultivation options are discussed in Section 5.2.

Conventional vegetable producers tend to think of some weed control practices as 'organic only', and not relevant to them (Sindel *et al.* 2011; Thompson 2012). However, rather than viewing conventional and organic weed control strategies (or 'productivity and sustainability') as mutually exclusive weed control approaches, Kristiansen *et al.* (1999) propose that purely conventional and purely organic approaches should instead be viewed at opposite ends of a continuum of crop (and weed) management options.

Considered in this way, weed management options commonly used in organic systems have the potential to expand the range of integrated weed management options available to conventional farmers, many of whom currently rely heavily on pre-emergent herbicides, or plastic mulch where this is relevant. For example, stale and false seedbed techniques (discussed in Section 5.12) provide effective weed control pre- and early post-plant with reduced herbicide requirements. Since cases of herbicide resistance have already been found that are relevant to Australian vegetable producers, and since there is a risk of further herbicide

[2] http://www.ewrs.org/pwc/proceedings.asp, accessed 12/5/14.

resistance developing (see Section 6.1.1), practices that allow farmers to reduce the amount of herbicide they use will extend the useful life of the limited range of herbicides currently available to them.

6. Innovations in weed control in vegetable crops

6.1. Factors influencing weed control practice change

6.1.1. Herbicide resistance

Repeated use of herbicides with the same mode of action can lead to herbicide resistance in weed populations (Preston 2000). It generally occurs when 'selection pressure' removes plants susceptible to the herbicide from the weed population, leaving those with resistance to the herbicide to survive, set seed, and increase the population of resistant plants (McGillion and Storrie 2006). Herbicide resistant weeds are found in all cropping regions of Australia, and the number of resistant species and geographic areas impacted by weed resistance is increasing (DAFWA 2010). Herbicide resistance in Australia is most notable amongst grass species, although a number of resistant broadleaf weeds have also been identified (Preston 2000). Monsanto (n.d.) reports that two ryegrass glyphosate resistant sites have been found in Victoria on vegetable farms, although the bulk of reported sites are in broadacre cropping, other forms of horticulture, and along fencelines and roadsides. Broadleaf weed herbicide resistance cases have been recorded in North America and Europe (Henderson 1998). For example, pigweed resistance to prometryne and linuron has been found in Canada (Swanton *et al.* 2009).

> *Continued use of the same herbicide can lead to development of resistant weeds or uncontrolled weed spectrums. A biotype of sowthistle resistant to several herbicide groups has recently been recorded in Queensland and northern New South Wales. There is a strong community desire for reduced pesticide use. Vegetable farmers need to be seen to be taking positive action in this regard. (Henderson 1998).*

The growing importance of herbicide resistance means that vegetable farmers need to be conscious not only of more effective and strategic use of herbicides, but also of integrating non-chemical techniques into their overall weed strategy. Vegetable farmers have a limited range of herbicide choices already, particularly for broadleaf species, and so resistance is an especially important issue. Examples of weeds that have developed resistance to herbicides available for vegetable production include:

- Annual ryegrass (*Lolium rigidum*) and crabgrass (*Digitaria sanguinalis*) resistance to fluazifop-p-butyl, quizafalop, clethodim and sethoxydim (Powles and Holtum 1990; Henskens *et al.* 1996; Hidayat and Preston 2001; Qld DAFF 2010; Malone *et al.* 2010). Three of these products, fluazifop-p-butyl, clethodim and sethoxydim, are registered in Australia for post-emergence grass weed control in lettuce crops (Qld DAFF 2010).
- Wild oat (*Avena* spp.) resistance to sethoxydim (Owen and Powles 2009).
- Capeweed (*Arctotheca calendula*) resistance to paraquat and diquat (Powles and Holtum 1990).

- Barnyard grass (*Echinochloa* spp.) resistance to clomazone outside of Australia (Pratley and Broster 2004; Pratley *et al.* 2008).
- Considerable research into resistance, and resistance minimisation strategies, for the important pre-plant knock-down herbicide glyphosate are also ongoing (AGSWG 2010).

The ability of vegetable farmers to control these and other weeds in their crop pre- and post-emergence may be impacted over time by resistance biotypes, and this may already be an issue in some areas. However the potential for herbicide resistant weed populations to develop has implications for pre-emergence broadleaf weed control in vegetables as well.

6.1.2. Changing climate

At the present time, little information is available regarding the specific impact of changing climate for weed management in Australian cucurbit crops. HAL has identified changing distribution and abundance of pests and weeds in Australian vegetable growing regions as an issue it will seek to address in its 'Horticulture Climate Change Action Plan' (HAL 2009).

The Australian Government-funded cooperative venture 'National Agriculture and Climate Change Action Plan' (NACCAP 2008) predicts in general terms changes in pest animal and weed issues for primary producers as a result of climate change. The potential implications for cucurbit producers include:

- Weeds that may be dispersed efficiently over longer distances (for example by wind, water or birds) may invade areas faster than weeds that rely on vegetative dispersal. This change may influence the distribution patterns of weeds already prevalent in cucurbit crops, or introduce new weeds.
- Changes in average temperature and rainfall across Australia may affect the distribution and density of weeds in cucurbit growing regions.
- 'Pre-emergent herbicides or herbicides absorbed by plant roots need soil moisture and actively growing roots to reach their target species. Drying winter and spring rainfall trends have the potential to reduce the effectiveness of pre-emergent herbicides such as triazines (NACCAP 2008).
- Changes in climate may actually make it easier for farmers in some regions to manage weeds, as their natural range contracts or shifts.

6.1.3. Environmental impacts of herbicide

Chemical use is particularly intensive in fruit and vegetable production in comparison with most other forms of agriculture, and many widely used weed and pest control practices have come under closer scrutiny over recent decades (Stringer 1998). High reliance on herbicides for weed control in Australian agriculture has raised environmental concerns regarding the short- and long-term fate of herbicide residues in the environment, chemical container disposal, herbicide impact on non-target systems and organisms (such as nearby waterways), and whether herbicide application practices can be improved, or agricultural reliance on herbicides be reduced, to make herbicide use more sustainable (Adkins and Walker 2000; ANRA 2007).

The challenge for farmers has been and will remain to reduce their reliance on herbicides while still controlling weeds effectively in their crop. Many of the practices that facilitate reduced and more sustainable herbicide use are discussed in Chapter 5, including crop competition, and living mulches and cover crops. Precision agriculture and weed mapping also have potential to reduce the amount of herbicide used on a farm. Chemical companies have also developed herbicides that are effective at lower rates and have a lower mammalian toxicity (Adkins and Walker 2000).

Many industries have introduced Quality Assurance (QA) or Best Management Practice (BMP) guidelines for their farmers to facilitate integrated and environmentally sustainable approaches to weed and pest management (Adkins and Walker 2000). In Western Australia, vegetablesWA (2007) have published a 'Good Practice Guide', which details approaches farmers can take to maintain yield and quality while reducing the environmental impact of production (although the current edition of the guide focuses on sustainable insect pest management rather than weed management). Similarly, Queensland Fruit & Vegetable Growers Ltd (Growcom n.d.) have published the 'Farmcare Code of Practice for Sustainable Fruit and Vegetable Production', although again this document (unsighted for this review but summarised in Growcom n.d.) appears to focus more on the impacts of pesticide and fertiliser use.

6.1.4. Plastic mulch disposal issues

While plastic mulch is still the most viable mulching technique for relevant crops, it is not a sustainable practice in the longer term (Wright pers. comm.). The use of plastic mulch is coming under increasing pressure, due largely to the environmental problems posed by disposal. Plastic mulch disposal options such as ploughing the mulch into the soil, burning or disposing at local land-fill sites are being progressively banned or restricted. They cause pollution and other local environmental problems, and are becoming less acceptable to the community (Henderson and Bishop 2000; Wright 2000; Limpus *et al.* 2012). 'Options for disposal of the mulch at the end of its useful life are becoming increasingly untenable around Australia with municipal authorities rejecting, restricting or increasing the costs of dealing with plastic mulch at their waste management plants' (Heisswolf and Wright 2010). In Bowen, Qld, for example, the local council stopped accepting plastic mulch at its local landfill facility, forcing farmers to dump used mulch down a disused mine shaft as a temporary solution (Olsen and Gounder 2001). The scale of this problem is reflected in the fact that in Australian vegetable production alone, an estimated 18 million metres of plastic mulch is used annually (Miao *et al.* 2013).

Despite its cost competitiveness, the longer-term future viability of plastic mulch in Australian vegetable production therefore appears doubtful – although farmers are still confident that plastic mulch will remain a viable option for some time (Sindel *et al.* 2011). Other mulches or options for managing weeds, diseases and pests, and soil moisture levels in the crop bed may, out of necessity, come into more widespread use. Organic and living/killed mulches are discussed in more detail in Sections 5.6 and Section 5.7. Some investigation has taken place to determine the viability of biodegradable mulch film as a replacement for conventional plastic mulch, and this product appears to show considerable promise (Limpus *et al.* 2012). Biodegradable mulch film is discussed further in Section 6.3.

6.1.5. Fumigation – an uncertain future

Methyl bromide use has been prohibited in Australia from 2005 as part of Australia's international obligation under the Montreal Protocol to restrict use of this and other ozone-depleting substances (DEWHA 2007). There are a number of alternative fumigants on the market in Australia, including Telone (1,3-dichloropropene plus chloropicrin), Metham (metham sodium) and EnviroFume (metham potassium) (Vock and Greer 2007). However, Henderson and Bishop (2000) questioned the long-term community acceptance of all forms of chemical soil fumigation, and expected these products to be phased out in addition to methyl bromide. Consequently, they argue that farmers should not rely on fumigation as a key factor in their overall weed control strategy, and that more socially acceptable alternatives will need to be developed. Fumigation is also an expensive crop management technique, and may be uneconomic in some vegetable crops (Qld DAFF 2012).

6.1.6. Socio-economic factors

There has been a tendency in Australian vegetable production of farm aggregation into fewer and larger, more professional farmers, who focus strongly on improving 'growing techniques, best management practices and quality produce' (Kelly 2007).

The implication for weed control is that the cost effectiveness of particular techniques may be partially dependent on farm scale. For example, larger scale farmers may find transported organic mulches to be a viable alternative to plastic mulch on a large area, whereas smaller farmers might prefer a crop cover organic mulch or plastic mulch. Many smaller farmers may prefer not to use any form of mulch due to cost, and pressure to remain profitable. The establishment and infrastructure costs for controlled traffic systems and permanent beds, farm hygiene, and thermal weed control, may be more easily absorbed by larger farmers. Crop rotation and green manure crops may also be more feasible on a larger farm, allowing farmers to diversify their production, rest some paddocks, and still maintain vegetable crops on some parts of their property all year round (or each growing season). Larger producers are also more likely to be able to justify on economic grounds investment in a modified IWM strategy that incorporates these and other emergent and novel weed management techniques (possibly including biodegradable and paper films, stale or false seedbeds, GPS and precision systems, and intra-row weeding equipment).

6.1.7. Technological development

Emerging crop management technologies are likely to change the way in which farmers manage weeds in their vegetable crop. Technologies discussed in this review include biodegradable mulch films (Section 6.3), biofumigant crops (Section 5.9.1) and precision technology (Section 8.3). The factors that will determine that rate of adoption of these and other emerging technologies will include their success in managing weeds and/or the crop, their ease of availability, their functionality and ease of use for farmers (perhaps with little outlay on new equipment), and their cost effectiveness.

6.2. Herbicide options

A search of the literature in the United States conducted as part of the HAL-funded project VG10048 (Sindel *et al.* 2011) suggested that a range of alternative herbicides may potentially be registered for use in cucurbit crops in Australia. Different options may also be available for Australia's other vegetable crops.

More detailed research into herbicide options is being carried out at a later stage of this project in consultation with farmers, industry representatives, and herbicide resellers. The results of this work will be included in the final report for this project. However, the earlier research (Sindel *et al.* 2011) did suggest that achieving registration of new herbicides would be difficult without significant industry support (e.g. HAL funding). This is due to the cost of registration, the relatively small size of the Australian industry, and the unwillingness of herbicide companies to wear registration costs without potential to recoup their investment.

6.3. Biodegradable mulch films

6.3.1. Polymer-based films

Biodegradable starch-derived polymer mulches are proposed as an alternative to polyethylene plastic mulches. They are designed to last for several months after laying, so that they maintain sufficient weed control and moisture retention during the life of the crop, but degrade to the extent that they may be cultivated into the field post-harvest, leaving no toxic residues in the soil (Heisswolf and Wright 2010; Limpus *et al.* 2012). Research in Italy suggests that annual waste reduction of approximately 400 kg per hectare is possible by using biodegradable mulch films instead of conventional plastic (Razza and Degli Innocenti 2012).

These mulches have been under evaluation in Australia for more than a decade, and are being used by some commercial farmers (Limpus *et al.* 2012). Though biodegradable polymer performed reasonably well as a replacement for plastic mulch in trials conducted several years ago, it was a cost-prohibitive substitute, at $3,300/Ha compared with $860/Ha for plastic. Other problems identified at that time included the difficulties of laying biodegradable mulch effectively with existing equipment, and many products 'failing the biodegradability test'

(Heisswolf and Wright 2010), generally by being only photodegradable (degrading as a result of exposure to sunlight). Even at that stage, however, polymer was considered the most promising alternative to plastic, assuming that price and laying difficulties could be overcome (Olsen *et al.* 2000; Table 5.1).

Since then, the price of biodegradable mulch has decreased significantly (due in part to manufacturing trials in Australia using local raw materials). It is now only about 30% more expensive than polyethylene mulch, including the retrieval and disposal costs associated with polyethylene (Heisswolf and Wright 2010; Limpus *et al.* 2012).

A HAL-supported trial of biodegradable mulch options was recently completed by the Qld Department of Agriculture, Fisheries and Forestry near Bowen, in North Queensland (Heisswolf and Wright 2010; Limpus *et al.* 2012). Several products were trialled, and are discussed below in more detail in Section 6.3.4.

Another biodegradable mulch option has been developed in the UK by Terraseed (2014). This product includes a top layer of degradable plastic and a second layer of absorbent material, with crop seeds placed in rows between the two layers. The product is laid out in the crop row, and when irrigated the seeds germinate through slits cut in the top degradable plastic layer. In addition to controlling weeds within the crop rows, Terraseed has additional benefits to farmers including moisture retention and reduced evaporation, ensuring that crops germinate evenly, and preventing soil contamination. As a degradable material, Terraseed may be cultivated into the soil after harvest (Terraseed 2014; HAL 2005). Terraseed does not appear to be in use in Australia at present, and was not evaluated in the Queensland trial (Heisswolf *et al.* 2010; Qld DEEDI 2010; Limpus *et al.* 2012).

6.3.2. Paper-based films

Paper-based mulches are commercially available in Australia. As with biodegradable polymer mulches, their environmental and management impact is potentially much less than conventional plastic mulch, as the mulch breaks down and can be incorporated into the soil after crop harvest (NT Department of Resources 2012). Nonetheless, paper mulch is considerably more expensive than conventional plastic mulch, and does not appear to be widely used. It is heavier, less flexible and more difficult to lay on the crop beds, and require alterations to mulch laying equipment (Qld DAFF 2012).

6.3.3. Biodegradable weed mats

A recent CSIRO project funded by RIRDC evaluated the potential of biodegradable weed mats produced from agricultural waste fibres (Miao *et al.* 2013). The mat is produced from straw fibres, and economic modelling suggests it can be price competitive with currently available polyethylene film. At the time of writing, only laboratory-scale production of the project had taken place, and horticultural field trials were required to confirm the product's suitability for vegetable production. However, preliminary analysis suggested that the product may be an effective alternative to polyethylene film.

6.3.4. Australian field trials

In early trials of biodegradable mulch options, Olsen *et al.* (2000) found that paper film had a number of disadvantages in comparison with standard plastic mulch, including its weight (being much heavier than plastic), cost of field application, a need to modify mulch applicators to prevent tearing while laying, tearing at plant, and a tendency to break down too quickly. These results were confirmed by more recent trials in the Northern Territory (NT Department of Resources 2012). These trials suggested that paper mulch is more difficult to lay than plastic mulch at the correct tension without tearing, as it does not stretch. Its durability is poor compared to plastic mulch; persistent winds can result in mulch tearing until the crop has covered the mulch. It was again found to break down too quickly (after about 8 weeks), particularly along the damp strip sitting above drip line irrigation. Lateral water movement on the crop beds under paper mulch is less than under plastic mulch, confining root distribution as the crop plants mature.

In contrast, Mater-Bi biodegradable polymer performed reasonably well, and apart from its cost-effectiveness it was considered by Olsen *et al.* (2000) to have potential to replace conventional plastic mulch. More recent trials of Mater-Bi by Qld DAFF (Heisswolf *et al.* 2010; Limpus *et al.* 2012) confirmed its performance, while finding that several other products tested at the same time did not meet the project's performance criteria. However, the research showed that Mater-Bi can be laid with most (but not all) conventional polyethylene-laying equipment, and that in cropping trials (where it was laid up to six weeks before planting), it performed adequately, being likely to provide adequate cover for up to four months assuming it was not damaged greatly by laying activities or by animals. Yields of several vegetable crops were comparable to polyethylene films, and good weed suppression was provided for the life of the crops. Farmers have reportedly noticed improvements in the quality of biodegradable mulch films over the course of the two trial projects in Qld (Limpus *et al.* 2012).

Nonetheless, current research suggests a number of technical limitations associated with Mater-Bi and other biodegradable mulch films, that may be overcome with more trial work (Sindel *et al.* 2011; Cirujeda *et al.* 2012; Heisswolf *et al.* 2012; Limpus *et al.* 2012):

- Modifications will be required to some plastic mulch laying equipment to lay Mater-Bi without significant damage.
- Farmers need to remain vigilant during laying to avoid damaging the mulch, as it is considerably thinner than conventional plastic. Early losses in bed coverage will occur of damage is incurred during laying.
- Hard ground may need to be irrigated before laying to avoid wheel damage to the mulch.
- The mulch should not be laid more than four weeks before crop planting. Crops that produce shade (such as cucumbers and melons) may extend the life of Mater-Bi by reducing photo-degradation.
- The product needs to be less than six months old (manufacturing date), and stored in a cool shaded area. Extensive sunlight exposure before use

accelerates biodegradation of the film and leads to loss of bed cover and increased weed density.

- The product may not perform well on some soil types. Thicker gauges of Mater-Bi will be better suited to cloddy or stony soils.
- Biodegradable mulch films may be more susceptible than conventional polyethylene to penetration by nutgrass plants.
- Farmers are concerned about the potential litter issue caused by biodegradable mulch films, as they break into large pieces and blow into neighbouring paddocks and properties.

Nonetheless, ongoing trial activity and decreases in price over the past decade suggest that biodegradable mulches such as Mater-Bi are getting closer to being a viable alternative for farmers to plastic mulch. The improved relative economic viability of biodegradable mulches in the near future may result from a growing supply in Australia (particularly as local manufacturing capacity increases). At the same time, disposal problems may increase the true cost of polyethylene relative to its biodegradable alternatives.

6.4. Innovations in weed control outside Australia

In addition to exploring current and innovative weed control techniques in Australia, this review has focussed on innovative practices and products being researched overseas. Some of these practices and products have been trialled in Australia, or are in limited use, while others are yet to be introduced in Australia. Innovations include:

- new herbicides (see Section 6.2);
- soil solarization (Stapleton *et al.* 2005; see Section 5.13.3);
- biofumigation (see Section 5.9.1);
- cover crops (Walters and Young 2010; see Section 5.7); and
- precision weeding, including precision agriculture and new cultivation implements (Melander *et al.* 2005; see also Sections 5.2 and 8.3).

The European Weed Research Society hosts regular workshops on innovations around the world in physical and cultural weed control, primarily involving organic approaches (e.g. Cloutier 2014)[3], and is a useful source of information in this area.

Nuffield Scholarship holder Tim Harslett conducted an overseas study tour and identified a number of emerging weed control methods in use around the world (Harslett 2008):

> *For weed control the focus was on developed and developing technologies of sensor-guided inter- and intra-row mechanical weeding, GPS logging of plant*

[3] Workshop abstracts dating back to 1998 are available for free download from http://www.ewrs.org/pwc/, Accessed 15/5/14. Various working groups of the EWRS address topics such as herbicide resistance, biocontrol, herbicide use optimisation, weed mapping, and weed management in vegetables.

> *placement to allow autonomous weeding, fumigants, ammonium- based sprays, mulches, crop rotation, planting density and spacing, pre-planting kill off, steaming, flaming, solarisation, night land-prep/planting, glass-house production and genetic modification potential.*

Many of these technologies are touched on throughout this review, and are in various stages of trial or implementation in Australia.

7. Knowledge and research gaps

In this section, we discuss gaps in current knowledge and research pertaining to weed impact, species, and management. In doing so, we have made a judgement based on the available literature of the importance to the industry of addressing the gap, and the feasibility of doing so successfully. This judgement is somewhat subjective, and certainly open to interpretation.

7.1. Gaps relating to the impact of weeds

7.1.1. Supporting vegetable production in the Top End

Vegetable production appears to be expanding in Australia's Top End, with farmers producing vegetables in the Northern Territory and the Ord River irrigation area. Research on weed management specific to these non-traditional vegetable growing regions of Australia may be required. The Top End climate of hotter and more humid conditions and a long wet season may result in different weed species of importance, and different best practices for weed management. As a result, some of the research on crop and weed management conducted in other parts of Australia may not be applicable to these farmers. These regions warrant specific research support from the industry, as their proximity to Asia may allow lucrative and expanding export markets to develop.

- *Importance to industry: medium*
- *Feasibility: medium*

7.1.2. Economic impact analysis

A thorough and detailed analysis of the economic impact of weeds on vegetable production is required, including the cost of managing weeds (Section 3.1), and crop losses arising from weeds as a result from reduced yield and crop quality (Sections 3.2 to 3.4). This research may involve fieldwork to determine yield declines in different vegetable crops arising from weeds, their impact on crop management, and analyses of the cost of control. Solid data on the economic impact of weeds will allow farmers to understand the true extent of their impact and why it is important to manage weeds effectively. It may also allow different weed management techniques to be compared on the basis of effectiveness and affordability. It is important to bear in mind, however, that many of the methods used to manage weeds have other crop benefits and so are implemented for a range of reasons. It can therefore be difficult to determine the true cost of weed control in a vegetable crop.

- *Importance to industry: high*
- *Feasibility: medium-low*

7.2. Gaps relating to important weeds

Research is needed to explore in more detail the specific impacts on vegetable production of the most significant weeds found in crops, and management approaches targeting these species. Based on work within cucurbit vegetable crops, Sindel *et al.* (2011) suggested that this research and extension activity might focus on fat hen, blackberry nightshade, caltrop/cathead, pigweed/purslane, African lovegrass, and nutgrass. However, the final report for this project may identify a different list of priority weeds, and will be a good guide for selection of species for specific weed impact research.

A greater understanding of the importance of these weeds in vegetable production is required. Issues of interest could include factors influencing germination and early growth, timing of emergence in field situations, optimising herbicide effectiveness, and methods for reducing seed set.

- *Importance to industry: high*
- *Feasibility: high*

7.3. Gaps relating to weed management practices

Sindel *et al.* (2011) suggested that a number of weed control techniques and innovations needed to be trialled thoroughly for their potential benefits, and then extended to vegetable farmers if they proved to be valid options in Australian conditions. These included:

- alternative herbicides,
- stale or false seedbeds,
- earlier pre-plant drip irrigation under plastic mulch,
- precision agriculture,
- using plastic mulch for more than one crop, and
- implementing effective farm hygiene strategies.

More specific gaps in research and technology are discussed in the next few sub-sections.

7.3.1. Herbicide availability

The review suggests that in-crop selective herbicides for use in brassica and lettuce crops are not available, meaning that farmers rely heavily on cultivation and hand weeding. Herbicide products may not be available to fill this niche, however, options from outside Australia should be explored through desk top research, as well as herbicides already registered in Australia for other purposes.

- *Importance to industry: high*
- *Feasibility: low*

7.3.2. Herbicide resistance

Some weed resistance to herbicides registered for use in vegetable crops has been identified in the literature, and this appears likely to become a bigger issue in the future as resistance has also been noted outside Australia (Section 6.1.1). Farmers need to be especially aware of the potential for resistance to selective herbicides to develop in grass weed species. More research may be necessary to survey and test for weed resistance within vegetable crops across Australia, to identify which herbicides are becoming less useful as a result of resistance, and which herbicide or non-herbicide management alternatives may provide economic alternatives.

- *Importance to industry: high*
- *Feasibility: medium*

7.3.3. Genetically modified vegetable crops

Glyphosate-tolerant crop varieties are now available for a number of broadacre crops (Section 8.2). Many Australian vegetable farmers may be interested in the development of glyphosate-tolerant vegetable varieties given the lack of in-crop selective herbicide options for weed management, particularly of broadleaf weeds (although we identified no such varieties being developed in our search of the literature). However, more research would need to be completed regarding the willingness of farmers to rely so heavily on glyphosate (or indeed other herbicides), and the willingness of the community to purchase vegetables grown from GM plants.

- *Importance to industry: medium-high*
- *Feasibility: low*

7.3.4. Hand weeding implements

Improvements to hand weeding implements may allow for more efficient hand weeding within vegetable crops, Since this is such a significant cost to many vegetable farmers, any improvement will have significant industry-wide benefits, even though farmers are generally reticent to use hand weeding except as a last resort. Related research in this area would also be 'low-tech' – relatively cheap, easy to implement, and with a potentially great return on investment.

- *Importance to industry: low*
- *Feasibility: high*

7.3.5. Crop rotation

The review suggests that more research is needed on the potential benefits of crop rotation as a weed management tool. This would include the ability of different crops to out-compete specific weeds in the field, and the potential for rotations to provide access to a wider range of weed management techniques, particularly for the use of different selective herbicide options. However, it is important to bear in mind that the results are often not easy to generalise – the benefits of crop rotation will be very site and crop-specific.

- *Importance to industry: medium*
- *Feasibility: medium*

7.3.6. Biodegradable mulch film

The literature suggests that the quality of biodegradable mulch films continues to improve, and they are also becoming more cost-effective relative to the conventional plastic mulch alternative. Continued research is needed on this technology to improve its effectiveness further, as it has the potential to replace conventional plastic mulch film with relatively little outlay on new equipment for farmers. It can also significantly reduce the environmental impact of vegetable growing, and make it easier for farmers to manage their paddocks post-harvest: mulch retrieval will no longer be necessary if it is designed to break down in place after harvest (see Sections 5.4.1 and 6.3). Biodegradable mulch films appear to be a much more promising mulch alternative for farmers than the various organic mulch options discussed in this review (Section 5.6).

- *Importance to industry: medium-high*
- *Feasibility: medium*

7.3.7. Cover crop mulches

Cover crop mulch systems are less effective than plastic mulch for weed control. However, the longer-term viability of these systems is still dependent on further research that may refine their ability to control weeds more effectively. Their viability may also depend on the comparative longer-term viability of plastic or biodegradable mulch films. If biodegradable mulch films develop to the extent that they become a viable replacement for conventional plastic, they will most likely become a mainstay of production in crops where plastic is currently used. In cover crop mulches, research is required to overcome poor soil contact with the root ball of the crop during planting, and to address nutrient tie-up and allelopathy impacts on the crop.

- *Importance to industry: low-medium*
- *Feasibility: medium*

7.3.8. Controlled traffic farming

The literature suggests that controlled traffic farming, generally operating in a permanent or semi-permanent bed system and utilising precision guidance technology, has a range of clear environmental and farm management benefits, including improved weed management by reducing weed seed stimulation. More work is required to trial and integrate this approach in vegetable farms in different parts of Australia, however the required precision agriculture technology may need to advance further (and reduce in cost substantially) before farmers consider it worth investing in.

- *Importance to industry: low-medium*
- *Feasibility: low-medium*

8. Lessons from other agricultural industries

8.1. Reduced or zero till systems

Reduced- and zero-till has become popular in broadacre cropping, and no-till farmer groups exist in South Australia, Victoria and Western Australia. The principles are well established, and discussed briefly in Section 5.8.2. A report recently completed for the GRDC by Llewellyn and D'Emden (2012) suggests that although zero-till cropping is not necessarily a new approach, uptake had been relatively slow and had only picked up in in the past couple of decades. By the time the research had been completed however, approximately 90 per cent of farmers in most regions had adopted a zero-till approach, with rapid adoption occurring since the late 1990s when the benefits of reduced soil disturbance, greater profitability and sustainability were realised by many farmers. 'Lack of observed benefits' and 'machinery constraints' were the main reasons for non-adoption. In the vegetable industry, Sindel *et al.* (2011) found that only about a quarter of vegetable farmers surveyed believed it would be feasible to reduce herbicide usage by implementing a low till system. Nonetheless, low or zero till systems have been shown to be feasible in some forms of vegetable production (Section 5.8.2), and the lessons of broadacre cropping industries may be highly relevant to vegetable production on further exploration.

8.2. Genetically modified crops

Genetically modified (GM) 'Roundup Ready' broadacre crops have been available since the 1990s, with options now including soybeans, alfalfa, corn, cotton, canola, and sugarbeets. These varieties contain in-plant tolerance of Roundup (glyphosate) herbicide, allowing use of this herbicide at various stages of growth. The approach means that farmers can be less reliant on other selective herbicides within their Roundup Ready crops, while reportedly achieving superior weed control. The technology also opens up opportunities to implement a zero till system (Monsanto 2014). A possible drawback of this approach is that it encourages over-reliance on glyphosate herbicide, to the extent that glyphosate resistant weeds develop within Roundup Ready crops. However, use of glyphosate in Roundup Ready crops is recommended only as part of an integrated strategy which employs a range of methods, to minimise the risk of resistant weeds developing (Monsanto n.d.).

8.3. Precision weed detection and control technology

Automated precision herbicide application has the potential to increase production in vegetable and other crops, reducing herbicide use and reliance on in-crop weed control methods such as hand weeding, and at the same time allowing robust herbicide rates to be used that have a much higher chance of controlling weeds (McCarthy *et al.* 2010; Ferrier and Craig 2011). Precision management of weeds involves detecting individual weed plants amongst a crop, and controlling them with targeted doses of herbicides. When carried out early in the life cycle of the weed, this technology has the potential to significantly increase crop yields. It also has the potential to improve the efficiency of weed management greatly, by averting the need for broadscale herbicide application or mechanical weed control (Young and Meyer 2012; Peteinatos *et al.* 2013). Sensor technology is being developed for use at a broader scale, for example mapping weeds in a whole field using aerial imaging. It is also being developed for use at a local level, for example using real-time weed recognition optical sensors attached to spray equipment (McCarthy *et al.* 2010; Young and Meyer 2012; Peteinatos *et al.* 2013).

At the time of writing the technology appeared to be largely reserved for broadacre cropping use (for example sugar cane, canola, wheat and barley; McCarthy *et al.* 2010; Ferrier and Craig 2011). However, trials in the US have reported 85-100% control of pigweed, blackberry nightshade and spotted spurge (*Chamaesyce maculata*) in a newly planted tomato crop (Young and Meyer 2012). Nonetheless, limitations of commercially available technology can include an inability to detect weed species against any surface other than bare soil, and difficulty operating under different conditions, such as time of day and crop life stage (McCarthy *et al.* 2010).

Weed detection and control may still be some way off in vegetable production for in-crop weed control. Nonetheless, products such as WeedSeeker® may allow for significant reductions of post-harvest or paddock 'clean-up' herbicide use, by spraying only those parts of the field where weeds are detected, rather than a blanket herbicide treatment (Ferrier and Craig 2011).

8.4. Herbicide resistance management

Considerable research has been undertaken on herbicide resistance and its impact on Australia's grains and cotton industries. The IWM manual for cropping systems (McGillion and Storrie 2006) includes a section on herbicide resistance. This includes information on how resistance develops, its occurrence and extent in Australia, and weed species at risk of developing resistance. Similar information is included in the WEEDpak for cotton production (Cotton CRC 2008). Much of the herbicide resistance work carried out in these industries will also be of relevance to vegetable crops, particularly where the work covers weed species and herbicides that are relevant to vegetable production.

8.5. Integrated Weed Management

IWM and the extension of IWM also appears to be a strong focus of the Australian grains and cotton industries. The Cooperative Centre for Australian Weed Management published an IWM manual for cropping systems (McGillion and Storrie 2006), which is due to be updated by the GRDC in 2014. This manual includes: information on the economic benefits of IWM; herbicide resistance; agronomic principles to enhance the benefits of weed control tactics (such as crop choice and competition, and controlled traffic farming); specific tactics for weed management; profiles of weeds commonly found in cropping; and case studies of successful IWM in different cropping zones.

In the Australian cotton industry, 17 years of extensive research on weed management in cotton production has been summarised in 'WEEDpak' (Cotton CRC 2008). This detailed document is available online, and many sections have been revised since initial publication. Topics covered include weed identification and information, integrated weed management, herbicide resistance, herbicide availability, farm hygiene, management of problem weeds, rotation crops, and herbicide damage information. This document is also summarised in the 2013 Australian Cotton Production Manual (CRDC 2013), which details IWM tactics relevant to cotton production, as well as critical success factors and herbicide resistance issues.

As has been noted already in this review, IWM appears to be fairly poorly developed on most Australian vegetable farms, with farmers focusing most of their attention on the management of pests, diseases and viruses in their vegetable crops, and perhaps not considering the links between weed and pest impact and management. However, a stronger focus on IWM has the potential to improve vegetable crop yield and quality, and have beneficial side-effects for pest and disease management, and soil health (see Section 5.14). There is therefore an opportunity to extend IWM practices more effectively to vegetable farmers, as has been undertaken in broadacre cropping.

8.6. Extension

The Grains and Cotton Research and Development Corporations (GRDC and CRDC) have produced a series of extension resources on weed identification and management (Blaesing 2013).

These include:

- A GRDC integrated weed management manual, which 'describes a broad range of chemical and non-chemical tactics for weed management aimed at reducing the weed seedbank and the selection pressure for resistance on herbicides' (McGillion and Storrie 2006). The manual is discussed further in Section 8.5.
- A CRDC 'Cotton Pest Management Guide', which includes a chapter on weeds. Topics include herbicide resistance in cotton farming systems, important weeds, weed management tactics, herbicide tolerant technology, a cotton weed control guide, list of herbicide names and marketers, and volunteer cotton (CRDC 2013).
- 'WEEDpak', an IWM guide for cotton production (Cotton CRC 2008). Discussed further in Section 8.5.
- CRDC and GRDC fact sheets, including information on weed management in the areas of brome grass control, glyphosate resistance, controlled traffic farming, weed control in wheel tracks, managing the weed seed bank, the benefits of crop rotation, and farm hygiene practices[4].

[4] Available at http://www.grdc.com.au/Resources/Factsheets *and* http://crdc.com.au/?post_type=publication&p=3090, Accessed 15/4/14

- A GRDC online 'Ute Guide' for weed identification, available either as a web-based tool, or a smartphone app[5].

At the time of writing, only one extension document addressing IWM in vegetable crops was available (Qld DAFF 2012), while there appeared to be no extension on management strategies for particular weed species (see Section 9.3.3). Blaesing (2013) recommends that relevant information from resources such as the GRDC and CRDC publications be used to design projects and resources for vegetable farmers. Many of the issues are likely to be the same, and so the resources listed above provide a useful starting point for improved integrated weed management extension within vegetable production.

[5] Available at http://www.grdc.com.au/Resources/Ute-Guides/Weeds, Accessed 15/4/14

9. Extension needs

9.1. Options for extension delivery

There are a range of personal and media information avenues available to organisations such as HAL in extending new crop protection techniques to vegetable farmers. Detailed evaluations of extension options in the vegetable industry could not be identified for this review, although limited work in this area was completed as part of our earlier cucurbit-specific project (Sindel *et al.* 2011). However, more extensive research has been completed on information sources available to farmers on weed management in the grazing industry (van der Meulen *et al.* 2006b; Sindel *et al.* 2013). Personal sources of information may include: other family members; neighbours; local 'expert producers'; field days and workshops; farmer organisations; government; spray contractors; weeds authorities; agricultural consultants; chemical company advisors; and retailers. Media sources may include: books; newspapers; industry newsletters and magazines; government fact sheets and booklets; retailer fact sheets and booklets; radio; TV; email; and the internet.

9.2. Preferred information sources

The research in the grazing industry suggests that the most highly rated form of personal or face to face information on weed management comes from expert sources; either weeds officers, spray contractors, or others recognised as experts in the region (such as experienced farmers). Field days and workshops were also very highly regarded (van der Meulen *et al.* 2006b; Sindel *et al.* 2013). Agricultural consultants such as private agronomists were considered somewhat useful information sources, although it is likely that graziers consult their agronomist far less frequently than vegetable farmers, given the different requirements of each production system. Preferred media information sources in the more recent of these two publications (Sindel *et al.* 2013) included weed best practice management guides, government fact sheets and booklets. Other media information sources used by farmers with some frequency include farmer and industry newsletters and magazines, rural newspapers, and the internet.

Our earlier research with Australian cucurbit producers (Sindel *et al.* 2011) suggested that the most preferred information source on weed management was commercial suppliers and their representatives, while other farmers and neighbours, and private agronomists and horticulturalists, were also highly favoured. Booklets and fact sheets, and industry publications, were the most highly regarded written sources of information. Farmers consulted during this project emphasised the importance of local resellers and horticulturalists, but suggested that there was a looming shortage of trained and experienced horticulturalists (at least in the Bundaberg district in Qld). Similarly, farmers noted that government horticultural and extension services had declined markedly in recent years.

9.3. Currently available extension sources

9.3.1. One to one extension services – private and government

Internet search suggests that vegetable farmers across Australia have ready access to private or reseller-based agronomic and horticultural advice. A range of companies employ agronomic staff or other experts that may offer advice on ground preparation, crop seed selection and weed management (including herbicide usage). Companies offering these services include (but are not limited to) Elders, Roberts, Serve-Ag, E.E. Muir and Sons, CRT, and Landmark. There are private agronomists and horticulturalists who are not affiliated with a reseller company, while the main herbicide distributors in Australia also employ staff in an advisory role.

Information on government-employed horticulturalists and extension staff is difficult to come by through web research. Most advice provided by various state governments across Australia appears to be available in internet-based form (discussed below). At least one vegetable extension officer appears to be employed by the Victorian Department of Environment and Primary Industries, but information could not be found on the Vic DEPI website[6]. In NSW, government-employed extension staff (Department of Primary Industries) are located at the National Vegetable Industry Centre at the Yanco Agricultural Institute, and at the National Centre for Greenhouse Horticulture in Gosford[7]. The Tasmanian Department of Primary Industries, Parks, Water and Environment employed a Vegetable Industry Facilitator for 18 months from 2010[8]. In South Australia, Primary Industries and Regions SA employs horticulture industry development officers[9]. Information on one on one vegetable extension services provided by government could not be found for Western Australia or the Northern Territory, although Section 9.4 details extension staff supported by HAL funding in these latter two locations at the time of writing.

The above suggests that one to one extension on weeds management will be best achieved by recruiting the assistance of private and reseller-based agronomists and horticulturalists. The nature of vegetable production suggests that many if not all farmers will be in regular consultation with an agronomist or horticulturalist. The findings from Sindel *et al.* (2011) also suggest that private consultants are a highly trusted information source.

9.3.2. Regional and state farmer groups

Other farmers and neighbours are a highly regarded source of information amongst vegetable farmers, and a common way for vegetable farmers to discuss crop management issues with their peers is at a farmer group meeting (Sindel *et al.* 2011). Preliminary discussion with industry contacts for this project suggests

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[6] http://www.vgavic.org.au/research_and_development/researchers/caroline_donald_dpi_victoria.htm
[7] http://www.dpi.nsw.gov.au/agriculture/horticulture/vegetables
[8] http://dpipwe.tas.gov.au/agriculture/publications-agriculture/tasmanian-vegetable-industry-facilitator-report
[9] http://www.pir.sa.gov.au/horticulture/contact_us

there are active farmer groups in many vegetable producing regions of Australia, for example a newly established group in the Lockyer Valley (Sippel pers. comm.). State-wide vegetable and/or farmer groups also exist. Regional and state-wide groups with an online presence are listed in Table 9.1.

Table 9.1 Regional and state-wide grower groups identified by internet research

Group or organisation name	Internet address
Bundaberg Fruit & Vegetable Growers, Qld	http://www.bfvg.com.au
Bowen Gumlu Growers Association, Qld: with an Industry Development Manager on staff	http://www.bowengumlugrowers.com.au
Growcom, Qld: with a pest management Industry Development Officer dedicated to maintaining off-label permits for chemicals, and an 'Infopest' chemical hotline	http://www.growcom.com.au/industry-services-2/pest-management/
New South Wales Farmers Association	http://www.nswfarmers.org.au/advocacy/cropping-and-horticulture/horticulture
Vegetable Growers Association of Victoria: publish a range of 'VegeNotes', including one on weed management	http://www.vgavic.org.au
Tasmanian Farmers and Graziers Association	http://www.tfga.com.au/industries/vegetables/
Vegetables WA: have produced a 'Pest and Disease Management' booklet, which includes information on weed control and the relationship between weeds and other pests	http://www.vegetableswa.com.au
NT Farmers	http://ntfarmers.org.au

9.3.3. Written and online services

A range of information guides and fact sheets are available on weed management in vegetables. Some of these deal explicitly with weeds, while others address weed management as an aspect of crop protection (for example, to eliminate or minimise host plants for viruses, pests and diseases). Examples of published resources are listed in Table 9.2. Examples of web-based information about vegetable crop management provided by government departments are listed in Table 9.3.

The AUSVEG website has an R&D outputs database within the Member's Area for vegetable farmers. This makes available full HAL project reports available, as well as 'VegeNotes', a regular information sheet which summarises current and recently completed research projects. AUSVEG also publishes two magazines, 'Potatoes Australia', and 'Vegetables Australia'. A comprehensive list of mobile phone and tablet apps relevant to vegetable farmers in Australia is also available on the AUSVEG website[10]. Apps relevant to weed management include several spray tank mix calculators and chemical product guides, Woody Weed Specialists (Dow AgroSciences), Weed ID (GRDC), APVMA, WeedSmart (Monsanto;

[10] http://ausveg.com.au/resources/smart-phone-apps.htm

herbicide resistance and weed seed bank management), and Weed Manager PLUS.

Table 9.2 Information guides on weed management in Australian vegetable crops

Title	Publisher, year published
A Guide to Effective Weed Control in Australian Brassicas	HAL, n.d.
Best practice IPM – Overview	Victorian DPI, 2010
Biosecurity Induction Manual for Bundaberg Horticultural Farms	Plant Health Australia, 2010
Weed management in lettuce crops	Qld DAFF, 2010
Integrated weed management components for vegetables	Qld DAFF, 2012
Managing weeds in broccoli, cauliflower and cabbage	Qld DAFF, 2013
Lettuce	Vic DEPI, 2013
Farm Biosecurity Manual for Northern Adelaide Plains Vegetable Growers	Plant Health Australia, 2010
Plant Biosecurity	HAL, n.d.
Brassica Integrated Pest & Disease Management	HAL, 2003
Vegetable Integrated Pest Management	NSW DPI, 2011
The Tasmanian Weed Handbook	Tas DPIPWE, 2011
Brassica Best Practice Integrated Pest Management	Vic DPI, 2010
Lettuce Best Practice Integrated Pest Management	Vic DPI, 2010
Weed Management	HAL, 2005
Pest and Disease Management	vegetablesWA, n.d.
Plant Biosecurity	HAL, n.d.
Tasmanian Washdown Guidelines for Weed and Disease Control	Tas DPIWE, 2004

Table 9.3 Online resources on weed management in Australian vegetable crops

Title	Publisher
Qld	http://www.daff.qld.gov.au/plants/fruit-and-vegetables
NSW	http://www.dpi.nsw.gov.au/agriculture/horticulture/vegetables
Vic	http://www.depi.vic.gov.au/agriculture-and-food/horticulture/vegetables
Tas	http://dpipwe.tas.gov.au/agriculture/plant-industries
SA	http://www.sardi.sa.gov.au/pestsdiseases/horticulture
WA	https://www.agric.wa.gov.au/vegetables/vegetables-western-australia
NT	http://www.nt.gov.au/d/Primary_Industry/?Header=Vegetables

9.4. HAL extension research and activity

HAL is funding a number of projects to maintain extension material delivery, build capacity within the vegetable industry, and support face to face extension (de Kock pers. comm.).

Current funding allows for ongoing production of the VegNotes series (VG12006), the Vegetables Australia magazine (VG12033), and supporting the

R&D outputs database maintained on the AUSVEG website (VG12071). HAL is also funding the update and republication of valuable vegetable industry resources (VG12087).

Current and recent capacity building projects funded by HAL seek to develop and extend to farmers best practice information on different aspects of crop management, all of which will involve effective weed management. These include:

- VG12008 – the EnviroVeg Program for promoting environmental best practice in the Australian vegetable industry
- VG13076 – Soil condition management – Extension and capacity building.
- VG13078 – Extension of Integrated Crop Protection information.

HAL is currently supporting an extension field officer for vegetable production and business management in the Northern Territory, employed through NT Farmers (VG12113). In Western Australia, HAL is funding a field extension officer (VG12026), and a second field officer to support vegetable farmers of Vietnamese origin (VG12024). Both are employed through vegetablesWA. Research suggests that face to face extension is the most highly valued and effective way to reach farmers, including vegetable farmers (Sindel *et al.* 2011; Coleman and Sindel 2014). And so these officers and others, supported by HAL, other industry bodies or government, are positioned to make an important contribution to improvements in weed management amongst vegetable farmers.

9.5. Gaps in extension

Sindel *et al.* (2011) made several recommendations to extend weed management information to farmers. Though focussing on cucurbits, these recommendations are just as relevant to all vegetable crops grown in Australia.

9.5.1. Weed species

Vegetable farmers need to understand the impact of particular weeds on their crop, in order to be motivated to implement targeted control strategies. This research needs to be carried out, and is discussed further in Section 7.2. The review of extension literature in this report did not identify any impact and management publications aimed at particular weed species within vegetable crops.

9.5.2. Current and innovative weed management methods

Further research into innovative weed management approaches, or ones with a relatively low uptake amongst vegetable farmers (Sindel *et al.* 2011), are recommended in Section 7.3. Information on the effectiveness of these issues and approaches should be extended to vegetable farmers if their effectiveness is validated. They include stale and false seedbeds, earlier pre-plant irrigation, precision agriculture, using plastic mulch and drip line infrastructure for more than one crop, and farm hygiene.

9.5.3. Integrated weed management

Relatively little extension information is available on IWM in vegetable crops, particularly in comparison to broadacre cropping such as grains and cotton (see Section 8.5). However, the recently commissioned HAL project VG13078 'Extension of Integrated Crop Protection information' is expected to go a long way towards addressing this current information gap, as IWM is an important aspect of broader ICP/ICM (see also Section 5.14).

9.5.4. Weed impact

Vegetable farmers need to have more information on the impact of weeds on their bottom line (yield and quality of the crop, and impact on farm management). The research recommended in Section 7.1 should therefore be extended to farmers, perhaps in the form of case studies.

9.5.5. Declining government extension services

Personal extension services available from government have been declining for a number of years across Australia, with many resources now delivered online. Some personal services are available in most states, however previous research suggests that vegetable farmers rely on their agronomist or product reseller instead. However, at the time of writing this review HAL had funded two extension officers in Western Australia, and one in the Northern Territory. There is an opportunity for HAL to fill the gap left by declining government extension services by funding or co-funding extension officers or industry development officers in other states and regions. Regional grower groups may be interested in a co-funding arrangement if they perceived the benefits of a local extension presence.

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Personal Communication

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Weed Management for the Vegetable Industry:

Appendix 2 – national survey questionnaire

Prepared for Horticulture Australia Limited (VG13079)

Paul Kristiansen, Michael Coleman, Chris Fyfe and Brian Sindel

University of New England

Armidale, NSW

August 2014

University of New England

Know-how for Horticulture™

Weed Management for the Vegetable Industry: Survey of Vegetable

Information Sheet for Survey Participants

We wish to invite you to participate in our research project, described below.

My name is Paul Kristiansen and I am conducting this research as part of a research project for Horticulture Australia Limited, ‘Weed Management for the Vegetable Industry’.

Aim of the Research
The University of New England is currently undertaking a research project on behalf of Horticulture Australia Limited (HAL) to identify better weed control options for vegetable crops.

Questionnaire
I would like to invite you to participate in our research by spending a few minutes completing this questionnaire, which has been sent to vegetable growers across Australia. I hope you will be involved.

Confidentiality
Any information or personal details gathered in the course of the study will remain confidential. No individual will be identified by name in any publication of the results. All names will be replaced by pseudonyms; this will ensure that you are not identifiable.

Participation is Voluntary
Please understand that your involvement in this study is voluntary and I respect your right to withdraw from the study at any time. You may discontinue the your completion of the questionnaire at any time without consequence and you do not need to provide any explanation if you decide not to participate or withdraw at any time.

Questions
The questions will not be of a sensitive nature and will deal with the impact and management of weeds within your vegetable crops, and industry research priorities.

Use of Information
The overall results of the research will be made available to growers like yourself through HAL and other grower representative groups. The data may also be used in future conference proceedings or journal articles. Your experience will help improve the capacity of the Australian vegetable industry to manage weeds more effectively. At all times, we will safeguard your identity by presenting the information in way that will not allow you to be identified.

Upsetting Issues
It is unlikely that this research will raise any personal or upsetting issue, but if it does you may wish to contact Lifeline on 131114.

Storage of Information
Questionnaire data will be stored electronically on a password protected computer in the researcher’s office at the University of New England’s School of Environmental and Rural Science. Only the research team will have access to the data.

Disposal of Information
All the data collected in this research will be kept for a minimum of five years after the completion of the project, after which it will be disposed of by deleting relevant computer files, and destroying or shredding hardcopy materials.

Approval
This project has been approved by the Human Research Ethics Committee of the University of New England (Approval No HE14-163, Valid to 27/05/2015).

Contact Details
Feel free to contact me with any questions about this research by email at paul.kristiansen@une.edu.au or by phone on 02 6773 2962

You may also contact my colleagues. Brian Sindel (bsindel@une.edu.au), Michael Coleman (michael.coleman@une.edu.au), or Chris Fyfe (cfyfe2@myune.edu.au)

Complaints

Should you have any complaints concerning the manner in which this research is conducted, please contact the Research Ethics Officer at:

Research Services
University of New England
Armidale, NSW 2351
Tel: (02) 6773 3449 Fax: (02) 6773 3543
Email: ethics@une.edu.au

Thank you for considering this request and I look forward to further contact with you.

Regards,

Paul Kristiansen

Weed Management for the Vegetable Industry: Survey of Vegetable

Online Implied Consent for Participants

Research Project

I have read the information contained in the Information Sheet for Participants and any questions I have asked have been answered to my satisfaction.

I agree to participate in this activity, realising that I may withdraw at any time.

I agree that research data gathered for the study may be published, and my identity will be unidentifiable due to the strict confidentiality explained in the information sheet.

I am over 18 years of age.

In preservation of anonymity, I understand that no name or signature is required of me to give consent. By pressing the **next** button below I am agreeing to participate in this study.

Weed Management for the Vegetable Industry: Survey of Vegetable

If you have **not** grown a vegetable crop in the past 3 years, you do not need to complete this survey. We thank you for your time.

If you have grown a vegetable crop in the last 3 years, please continue by selecting the *Next* button below.

Weed Management for the Vegetable Industry: Survey of Vegetable

Section 1: Your Farm

1. What is your post code?

2. How many years experience do you have growing vegetables?

3. Please indicate the total area you have under vegetables this year.

Hectares:

OR Acres:

4. Is vegetable production your sole agricultural pursuit?

Yes

No

If no, what other forms of agricultural production are you involved in?

Section 1: Your Farm (continued)

5. Please indicate up to five of the main vegetable crops you have grown <u>over the past three years</u>, and estimate the <u>average</u> area per season planted with each crop.

Vegetable crop 1

Crop name

Area - Hectares

OR Area - Acres

Vegetable crop 2

Crop name

Area - Hectares

OR Area - Acres

Vegetable crop 3

Crop name

Area - Hectares

OR Area - Acres

Vegetable crop 4

Crop name

Area - Hectares

OR Area - Acres

Vegetable crop 5

Crop name

Area - Hectares

OR Area - Acres

Weed Management for the Vegetable Industry: Survey of Vegetable

Section 2a: The Impact of Weeds

Please answer this section only in relation to your most important vegetable crop.

6. Please name your most important vegetable crop.

7. For your *most important* vegetable crop, which weeds cause the greatest problems, and what types of impact do they have?

(Please rank the weeds in order of importance, with most important listed first. You may list up to five weeds)

Name of most important weed

Types of impact *(please select all that apply)*

- ☐ Reduction in crop *yield*
- ☐ Reduction in crop *quality*
- ☐ Management of crop made more difficult or more costly

Other *(please specify)*

Name of 2nd most important weed

Types of impact *(please select all that apply)*

- ☐ Reduction in crop *yield*
- ☐ Reduction in crop *quality*
- ☐ Management of crop made more difficult or more costly

Other *(please specify)*

Name of 3rd most important weed

Types of impact *(please select all that apply)*

- ☐ Reduction in crop *yield*
- ☐ Reduction in crop *quality*
- ☐ Management of crop made more difficult or more costly

Other *(please specify)*

Name of 4th most important weed

Types of impact ***(please select all that apply)***

- [ ] Reduction in crop *yield*
- [ ] Reduction in crop *quality*
- [ ] Management of crop made more difficult or more costly

Other *(please specify)*

Name of 5th most important weed

Types of impact ***(please select all that apply)***

- [ ] Reduction in crop *yield*
- [ ] Reduction in crop *quality*
- [ ] Management of crop made more difficult or more costly

Other *(please specify)*

Weed Management for the Vegetable Industry: Survey of Vegetable

Section 2b: Current Weed Control Practices

Please answer this section only in relation to your most important vegetable crop.

8. For your *most important* vegetable crop, what methods do you currently use to control weeds?

Please score each of the methods you are using now, on a scale of 1 to 5, where '1' is not effective or affordable, and '5' is highly effective or affordable.

	Affordability	Effectiveness
Herbicides (in-crop pre-emergent)		
Herbicides (in-crop post-emergent)		
Herbicides (in-fallow)		
Herbicides (inter-row shielded)		
Chipping and hand weeding		
Tillage/cultivation before sowing/planting		
Tillage/cultivation (inter-row)		
Farm hygiene and quarantine		
Plastic mulch		
Biodegradable mulch		
Organic mulch (e.g. woodchip, sawdust)		
Crop rotation		
Increase plant density		
Permanent beds/controlled traffic farming		
Precision agriculture/GPS guidance technology		
Weed sensor technology		
Pre-irrigate and spray/till ('stale/false seedbed')		
Other		

Please specify other

9. What, if any, are the major problems you have with weed control in your most important vegetable crop?

10. What are the critical factors for achieving success with weed control in your most important vegetable crop?

11. We are interested in finding out about a wide range of weed management methods and systems in vegetables. In order to do this, we would like to know about other weed management approaches you use.

Out of your five most important crops, is there one crop which has a different weed management approach to your most important crop?

- ◯ Yes
- ◯ No

Weed Management for the Vegetable Industry: Survey of Vegetable

Section 3a: The Impact of Weeds

Please answer this section only in relation to your other weed management approach.

12. Please name the vegetable crop where you use this other weed management approach.

13. For your *other weed management approach*, which weeds cause the greatest problems, and what types of impact do they have?

(Please rank the weeds in order of importance, with most important listed first. You may list up to five weeds)

Name of most important weed

Types of impact *(please select all that apply)*

- ☐ Reduction in crop *yield*
- ☐ Reduction in crop *quality*
- ☐ Management of crop made more difficult or more costly

Other *(please specify)*

Name of 2nd most important weed

Types of impact *(please select all that apply)*

- ☐ Reduction in crop *yield*
- ☐ Reduction in crop *quality*
- ☐ Management of crop made more difficult or more costly

Other *(please specify)*

Name of 3rd most important weed

Types of impact *(please select all that apply)*

- ☐ Reduction in crop *yield*
- ☐ Reduction in crop *quality*
- ☐ Management of crop made more difficult or more costly

Other *(please specify)*

Name of 4th most important weed

Types of impact ***(please select all that apply)***

- [ ] Reduction in crop *yield*
- [ ] Reduction in crop *quality*
- [ ] Management of crop made more difficult or more costly

Other *(please specify)*

Name of 5th most important weed

Types of impact ***(please select all that apply)***

- [ ] Reduction in crop *yield*
- [ ] Reduction in crop *quality*
- [ ] Management of crop made more difficult or more costly

Other *(please specify)*

Weed Management for the Vegetable Industry: Survey of Vegetable

Section 3b: Current Weed Control Practices

Please answer this section only in relation to your other weed management approach.

14. For your *other weed management approach*, what methods do you currently use to control weeds?

Please score each of the methods you are using now, on a scale of 1 to 5, where '1' is not effective or affordable, and '5' is highly effective or affordable.

	Affordability	Effectiveness
Herbicides (in-crop pre-emergent)		
Herbicides (in-crop post-emergent)		
Herbicides (in-fallow)		
Herbicides (inter-row shielded)		
Chipping and hand weeding		
Tillage/cultivation before sowing/planting		
Tillage/cultivation (inter-row)		
Farm hygiene and quarantine		
Plastic mulch		
Biodegradable mulch		
Organic mulch (e.g. woodchip, sawdust)		
Crop rotation		
Increase plant density		
Permanent beds/controlled traffic farming		
Precision agriculture/GPS guidance technology		
Weed sensor technology		
Pre-irrigate and spray/till ('stale/false seedbed')		
Other		

Please specify other

15. What, if any, are the major problems you have with weed control in your other weed management approach?

16. What are the critical factors for achieving success with weed control in your other weed management approach?

Weed Management for the Vegetable Industry: Survey of Vegetable

Section 4: Other Weed Control Methods

17. Are you satisfied with the level of weed control in your vegetable crops?

- Yes
- No

18. Are you considering trying any new or innovative weed control methods in your vegetable crops?

- Yes
- No

If yes, please list the method/s, and briefly describe why you are considering using the method/s.

19. Are you aware of any innovations or practices used in the production of crops in other industries that should be used more widely to manage weeds in vegetable crops?

- Yes
- No

If yes, please provide details of the weed management practices and the cropping industry they are used in.

Section 5: Vegetable Industry Research Priorities

20. Should further research be carried out in the following areas?

	Yes	Unsure	No
Identifying new **herbicides** for weed control in vegetable crops	○	○	○
Developing **economic replacements** for polyethylene plastic mulch	○	○	○
Improving **tillage** practices and equipment	○	○	○
Determining the benefits to vegetable growers of **controlled traffic farming** and **precision agriculture**	○	○	○

21. Please describe other areas of research and development that you believe should be given priority to improve the management of weeds in vegetable crops.

Weed Management for the Vegetable Industry: Survey of Vegetable

Section 6: Vegetable Grower Education and Extension Needs

22. Which sources of information about weed management do you currently use?

(Please tick all that apply)

- [ ] Commercial suppliers and representatives
- [ ] Government agronomists and horticulturalists
- [ ] Private agronomists and horticulturalists
- [ ] Government extension professionals
- [ ] Workshops and field days
- [ ] Conferences and courses
- [ ] Other farmers/neighbours
- [ ] Booklets and fact sheets
- [ ] Industry newsletters or magazines
- [ ] Industry web sites
- [ ] Government web sites
- [ ] Newspapers
- [ ] Other

Please specify other

23. Which of these sources of information about weed management do you trust the most?

24. In what areas do you feel you need more information on weed management for your vegetable crops?

25. How would you prefer to receive this information?

26. Are you satisfied with current provision of weed management information to vegetable growers?

- ◯ Yes
- ◯ No

If not, what improvements are needed?

Weed Management for the Vegetable Industry: Survey of Vegetable

Section 7: Other Issues

27. Are there any changes to current government regulations that may improve your capacity to manage weeds in vegetable crops?

28. Do you have any other comments about weed management in vegetable crops?

Weed Management for the Vegetable Industry: Survey of Vegetable

Thank You

We greatly appreciate your time and effort in completing this survey for us.

If you would like to find out about the results of this research, please enter your email address below *(optional)*.

Please press the *Done* button below to submit your completed response.