Integrated weed management

for the Australian vegetable industry

Introduction

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Introduction

Weeds are a persistent problem in Australian vegetable crops. Their significant impacts can include:

- increased costs in growing the vegetable crop;
- reduced crop yield and quality due to weed competition;
- contamination of produce, and hosting of crop pests and diseases;
- difficulties harvesting; and
- reduced crop sale price.

Over-reliance on the relatively limited range of herbicides registered for vegetable crops can select for certain weed species, have negative impacts on soil biology and human health, and increase the risk of herbicide resistant weed populations emerging on vegetable farms.

A number of features of vegetable production systems often favour rapid weed germination and growth. These include frequently disturbed soil, irrigation, and addition of large amounts of nutritional inputs.

As part of a four year research and extension project funded by the Hort Innovation Vegetable Fund (VG15070), the University of New England has published the Australian vegetable industry's first comprehensive integrated weed management (IWM) manual.

Within these pages, we provide information on the impacts of weeds, the principles of IWM, and the various methods that may be included in an IWM strategy depending on crops grown and farm circumstances.

We have also worked with Australian vegetable growers to develop case studies on how IWM may be implemented effectively in different ways to reduce the impact of weeds, and ecology and management guides that address different priority weeds of the industry.

We hope that you find this information useful.

Associate Professor Paul Kristiansen

Project leader (VG15070 - A strategic approach to weed management for the Australian vegetable industry)

University of New England

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This manual does not contain a complete statement of all relevant legal obligations. You should seek your own legal advice as to both legislative and general legal obligations, in particular those legal obligations rising under environmental laws and the general laws of negligence.

List of Resources

Integrated weed management for the Australian vegetable industry has been made available as a series of standalone publications. Each of these addresses a different aspect of weeds and their management. Below is a list of the publications included.

This publication should be cited as: Kristiansen, P., Coleman, M., Sindel, B., and Fyfe, C. 2021. Integrated weed management for the Australian vegetable industry. Introduction. University of New England, Armidale.

v 1.0; May 2021.

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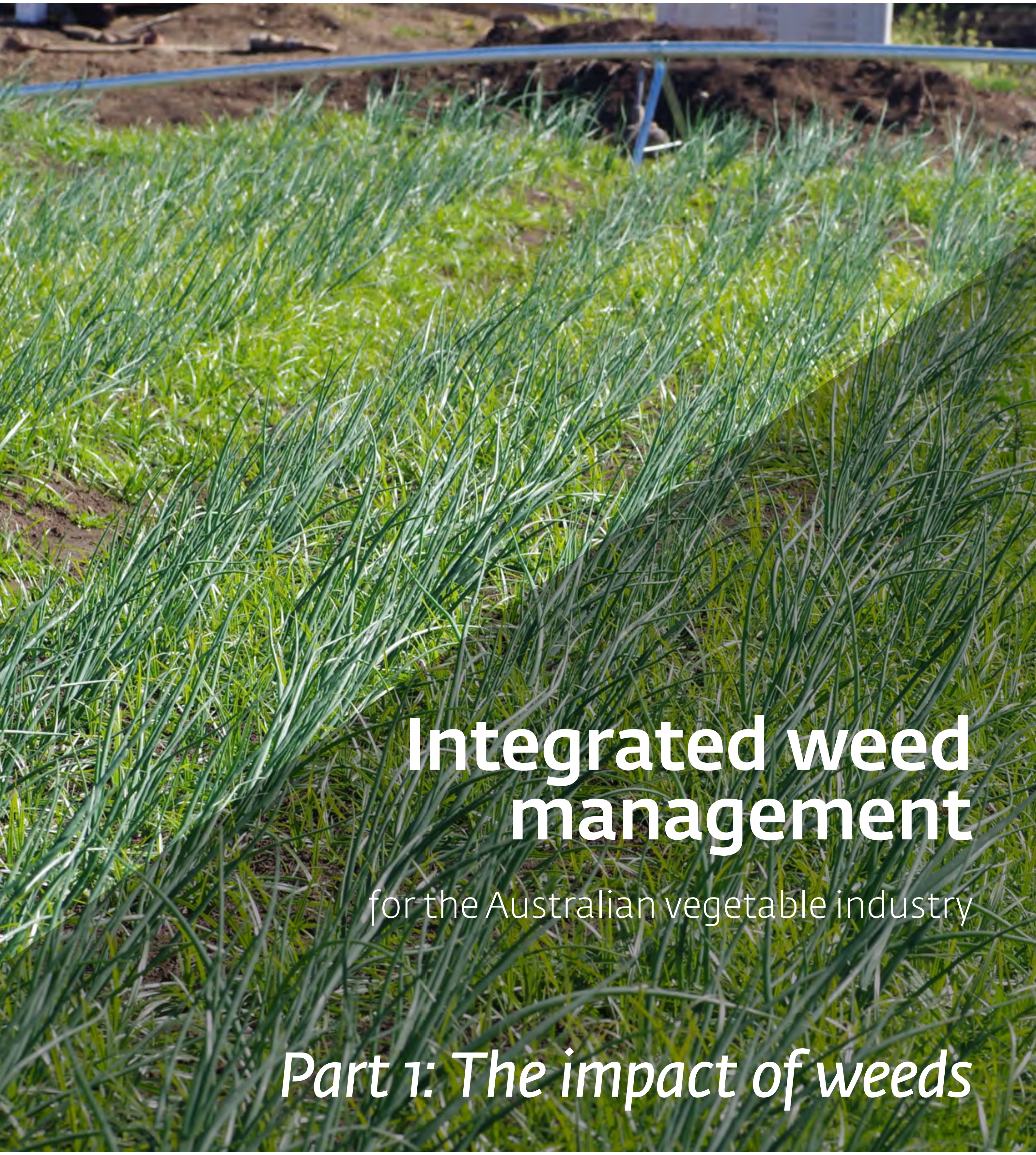

Integrated weed management

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Part 1: The impact of weeds

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Table of Contents: Part 1

The impact of weeds

- Weeds are a persistent problem for many vegetable producers in Australia.
- Common features of vegetable production systems include frequent cultivation that results in highly disturbed soil, frequent irrigation, and the addition of large amounts of fertiliser inputs to maximise crop growth. These factors mean that the potential for weed growth is high.
- Weeds therefore have significant impacts on vegetable production:
    - increasing the cost of growing the vegetable crop;
    - reducing crop yield through weed competition;
    - reducing crop quality through competition and contamination of produce, and hosting of crop pests and diseases;
    - reducing crop sale price and farm profitability; and
    - negative impacts on general farm management.
- Weeds also make crop management more difficult by impacting on the effectiveness of pest management and making harvesting more difficult.
- The most important weeds of Australian vegetable production are generally heavy seedling annual broadleaf species. Some examples include: fat hen (*Chenopodium album*), dwarf nettle (*Urtica urens*), mallow (*Malva parviflora*), pigweed (*Portulaca oleracea*) and amaranth (*Amaranthus* spp.). Grass and grass-like weeds are often more easily controlled using selective herbicides. Tuberous weeds such as nutgrass (*Cyperus rotundus*) and oxalis (*Oxalis* spp.) can also be major weeds on vegetable farms.
- Management guides specific to a range of the most prominent weeds accompany this Manual.

Why are weeds a problem in vegetable production?

Most vegetable crops in Australia are grown on intensively cropped land. Many vegetable growers consider that weeds are manageable on their farm, and that pests, viruses and diseases are a more significant crop protection issue.

However, when they are not managed effectively, weeds can have a significant impact on vegetable crop productivity. The potential for weed growth in vegetable production is high, due to a few characteristics of this production system:

- frequent cultivation that results in highly disturbed soil;
- irrigation (particularly furrow or flood irrigation); and
- the addition of large quantities of fertilisers before planting and during the growing period.

Figure 1-1. The wild radish (Raphanus raphanistrum) *visible within this carrot crop illustrates the potential for weeds to become a significant burden in the highly disturbed, irrigated and fertilised soils common to vegetable production (Location: Myalup, Western Australia).*

Figure 1-2 This cut-leaf salad crop near Richmond, Tasmania, is well managed for weeds. However the short stature of the crop plants and the method of harvest leaves the crop vulnerable to weed competition and contamination of produce, if weeds were allowed to establish in large numbers (Location: Richmond, Tasmania).

What are the impacts of weeds on vegetable crops?

Increased management expenses

Effective weed management requires significant time, effort and resources on Australian vegetable farms.

Some expenses may include:

- mulches;
- herbicides and other chemicals;
- fuel, machinery and other equipment (Figure 1-3);
- labour, including field staff, contractors and agronomists (Figure 1-4); and
- cash crop/cover crop seed or seedlings.

Figure 1-3 Machinery comprises a large proportion of weed management expenses on vegetable farms, through purchase, maintenance, and running expenses (Location: Richmond, New South Wales).

Figure 1-4 Hand weeding is a significant contributor to the high cost of labour that is associated with weed management in vegetable production (Location: Gatton, Queensland).

Reductions in crop yield

Table 1-1 How do weeds reduce vegetable crop yield?

Impact	Description and examples
Direct competition	Weeds may directly compete with vegetable crops for water, soil nutrients, light and space.
Competition during early crop life	Heavy weed competition during the early stages of the crop will result in the largest yield reductions. This makes it particularly critical to manage weeds immediately before planting or sowing the crop, and early in the crop life cycle, although effective weed control at all stages will help to reduce the weed burden over time. Vegetable crops with a longer growing season are especially vulnerable to weed invasion and yield reductions.
Competition due to poor fallow management	Poor management of weed outbreaks during fallow periods can reduce the yield of the subsequent cash crop, by extracting moisture and nutrients from the soil (Figure 1-5).
Impact of weed management activities on the crop	Essential weed control activities can themselves reduce crop yield, if not implemented correctly. Examples include herbicide spray drift, damage to crop roots associated with tillage between or within crop beds, as well as damage to crop roots and/or plants resulting from hand weeding. In some cases, growers may need to accept some crop damage in order to bring a significant weed problem under control.
Harvest difficulties	Where thorned or especially dense weed infestations are present, it may be difficult to successfully harvest all of the crop.
Reduction in 'marketable yield'	Weeds may impact both on the 'absolute yield' of a vegetable crop (the final quantity of output the crop), as well as on its marketable yield (the proportion of output that is suitable for sale; Figure 1-6). Reductions in marketable yield due to weed infestation may occur as a result of contamination or staining of the crop fruit or produce.

Figure 1-5 Heavily weed infested post-harvest and fallow paddocks can reduce the yield of subsequent vegetable crops, not only by taking resources from the field during the non-crop period, but also by increasing the weed seed bank and increasing seed germination in the subsequent cash crop (Location: Werribee, Victoria).

Figure 1-6 Fruit from blackberry nightshade (Solanum nigrum) *can reduce the marketable yield of a number of vegetable crops by staining the produce. In the case of processed peas* (Pisum sativum), *blackberry nightshade fruit are capable of contaminating the harvested peas as their comparable size can machine sorting difficult.*

Reductions in crop quality - pest and disease hosting

How do weeds reduce vegetable crop quality?

- Hosting diseases and viruses which negatively impact vegetable crops.
- Allowing viruses and diseases to survive in the paddock in between cash crop periods.
- Hosting insect pests which directly impact vegetable crops while also able to carry diseases and viruses into the vegetable crop.
- Broadleaf weeds that bear some similarity to vegetable crops are the most likely to host crop diseases, viruses and insect pests.

Weed management is therefore an important aspect of Integrated Pest Management in vegetable production.

Weeds are capable of hosting a variety of pests, diseases and viruses that impact on both the yield and the quality of a range of Australia's vegetable crops. This is particularly true of broadleaf weeds that share certain characteristics with crop plants (Figures 1-7 and 1-8).

This manual should therefore be read alongside relevant pest, disease and virus management resources for vegetable production (such as those available through the SoilWealth/ICP project), to provide growers with the background to implement an effective Integrated Crop Protection (ICP) program.

Pest, disease or virus issues often start in a weed infestation adjacent to or within the vegetable crop. When host weeds are not sufficiently controlled they may act as infection reservoirs for pests and diseases to spread within crops, or provide a bridge for pests and diseases to persist between cash crop growing periods.

Figure 1-7 Wild cucurbit species such as Afghan melon (Citrullus lanatus) *host a range of important cucurbit viruses in Western Australia (Location: Myalup, Western Australia).*

Figure 1-8 Wild radish (Raphanus raphanistrum) *hosts a number of vegetable crop pests and diseases that can impact on brassicas and cucurbits (Location: Adelaide, South Australia).*

Table 1-2 includes examples of vegetable crop pests and diseases, and impacted crops.

Table 1-2 Pests, viruses and diseases in Australian vegetable crops that are known to be hosted by weeds.

Pest, virus or disease	Vegetable crop/s impacted
Capsicum chlorosis virus	Capsicum
Various cucurbit viruses: zucchini yellow mosaic virus, papaya ringspot virus, squash mosaic virus, watermelon mosaic virus, and cucumber mosaic virus	Cucurbits
Lettuce necrotic virus	Lettuce
Powdery mildew (*Erysiphe heraclei*)	Carrot, parsnip
Black leg (*Phoma lingam*)	Broccoli, cabbage
Grey mould (*Botrytis cinerea*)	Tomato, bean, capsicum, cucumber, brassica and lettuce
Gummy stem blight (*Didymella bryoniae*)	Pumpkin, rockmelon
Fungal root rot (including *Pythium*, *Rhizoctonia* and *Fusarium*)	Various
Black root rot (*Thielaviopsis basicola*)	Bean, carrot, lettuce
Dry leaf spot (*Xanthomonas camestris* pv. vitians)	Lettuce
Cavity spot (*Pythium violae*)	Carrot
Clubroot (*Plasmodiophora brassicae*)	Brassica
White blister (*Albugo candida*)	Brassica
Snails and slugs	Various
Cutworm (several types)	Carrot
Vegetable weevil (*Listoderes difficilis*)	Carrot, tomato, celery and potato
Rutherglen bug (*Nysius vinitor*)	Lettuce
Mites (several species)	Various
Silverleaf whitefly (*Bemisia tabaci*)	Various
Aphids (several types)	Various, e.g. lettuce, potato, corn and cabbage
Thrips (*Thrips* spp.)	Various, e.g. lettuce, tomato, capsicum, chilli

Weeds that are capable of hosting one or more of these pests, viruses and diseases include many of the common weeds found in vegetable production, for example:

- Common sowthistle, *Sonchus oleraceus*;
- Wild radish, *Raphanus raphanistrum*;
- Potato weed, *Galinsoga parviflora*;
- Pigweed, *Portulaca oleracea*;
- Marshmallow, *Malva parviflora*;
- Blackberry nightshade, *Solanum nigrum*;
- Amaranth, *Amaranthus* spp.;
- Wild turnip, *Brassica tournefortii*; and
- Prickly lettuce, *Lactuca serriola*.

Impacts on crop and farm management

There are several factors which are associated with the impact of weeds on crop and farm management (Table 1-3). Issues such as accurate weed identification, strategic crop selection and the industry-wide lack of registered herbicides are indirect but important aspects of weed management.

Table 1-3 Summary of weed impacts on crop and farm management.

Impact	Description and examples
Weed identification	Paddock inspection and hand weeding within vegetable 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. Incorrect identification may also result in other issues such as using the wrong herbicide.
Weed management in different vegetable crops	Some vegetable crops present a more significant and ongoing weed management challenge to growers than others. Where the crop canopy is slow to close (e.g. winter leafy crops), or remains relatively open until harvest (e.g. onions, leeks), weeds will have a much greater chance of establishing and competing vigorously (see 'Crop competition' in Part 3 of this manual).
Crop selection	The presence of some weed species on the farm, particularly in large numbers, may limit the vegetable crop choices available to growers. Extensive management of the field to reduce the weed seed bank over several years may be required. Rotating to non-vegetable crops for part of the year may help, by providing different herbicide options (Figure 1-9; see also 'Crop rotation' in Part 3 of this manual).
Harvest and post-harvest interference	Particularly heavy weed 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 (Figure 1-10). Weeds with sharp spines or burrs can also slow harvesting. Nutgrass (*Cyperus rotundus*) can pierce plastic mulch film and make post-harvest removal more difficult and expensive.
Lack of registered herbicides	Weed management in vegetable crops is made difficult for growers by a relative lack of registered herbicides for controlling weeds within the crop rows. This is particularly the case for broadleaf weed management after crop emergence. As a result, growers are required to rely more heavily on non-herbicide control methods such as tillage, hand weeding, plastic mulch (depending on crop) and a variety of other methods. These can be more time-consuming and expensive, but also used together effectively.

Figure 1-9 Rotating cucurbit production with sugar cane gives growers in Central Queensland access to more herbicide options to control broadleaf weeds. (Location: Childers, Queensland).

Figure 1-10 Wireweed (Polygonum aviculare) *is capable of forming a dense mat of strong branches which can interfere with harvesting machinery in certain crops, as well as post-harvest tillage. These activities can become more time-consuming and expensive in heavily infested paddocks (Location: Richmond, Tasmania).*

"When they become a larger problem, weeds can have a significant impact on vegetable crop productivity."

What weeds are present on Australia's vegetable farms?

The most problematic weeds of vegetable production are heavy-seeding broadleaf weeds, with the exception of the sedge, nutgrass (*Cyperus rotundus*) and oxalis (*Oxalis* spp.). These broadleaf weeds are usually relatively short living (either annual or biennial), although some long lived (perennial) species were also identified as problems in some regions or on some farms (Figure 1-11).

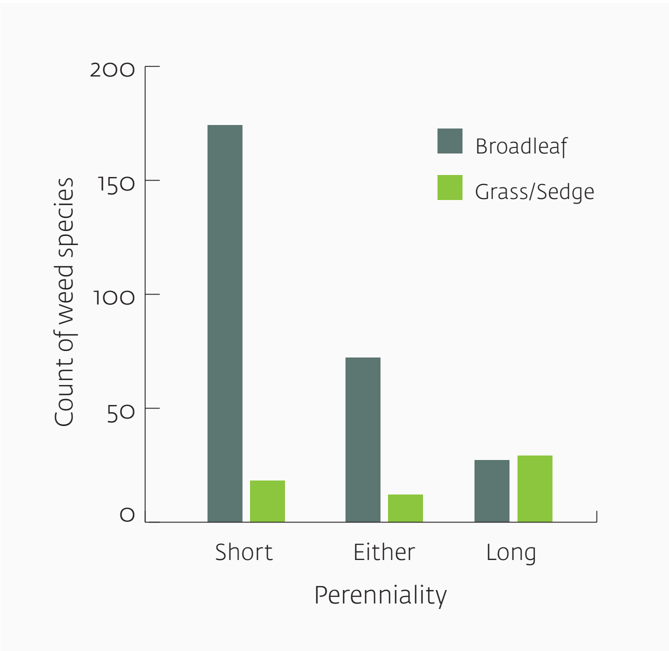

Figure 1-11 Count of distinct broadleaf and grass/sedge weed species identified during industry consultation, classified by perenniality: short (annual and/or biennial), either (variable or uncertain perenniality), or long (perennial).

Integrated weed management guides are available for eleven of the most common and problematic weeds of vegetable production in Australia:

- Fat hen (*Chenopodium album*);
- Dwarf nettle (*Urtica urens*);
- Marshmallow (*Malva parviflora*);
- Nutgrass (*Cyperus rotundus*);
- Pigweed (*Portulaca oleracea*);
- Amaranth (*Amaranthus* spp.);
- Wild radish (*Raphanus raphanistrum*);
- Blackberry nightshade (*Solanum nigrum*);
- Common sowthistle (*Sonchus oleraceus*);
- Chickweed (*Stellaria media*); and
- Potato weed (*Galinsoga parviflora*).

Figure 1-12 Fat hen (Chenopodium album).

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Part 2: The principles

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Table of Contents: Part 2

Integrated Weed Management in Vegetable Production

Nearly all Australian vegetable growers integrate a number of weed control methods into a weed management strategy.

No single method alone will effectively manage weeds in the crop during the entire growing season.

This is known as Integrated Weed Management (IWM).

*Figure 2-1. The potential for herbicide resistant populations of weeds such as wild radish (*Raphanus raphanistrum*) to occur on Australian vegetable farms appears to be high, given that resistance is widespread in Australian broadacre crops. IWM can help address herbicide resistance, through a diversity of appropriately-timed weed control techniques that reduce overall reliance on herbicide (Location: Gawler, South Australia).*

*Figure 2-2. Seed of blackberry nightshade (*Solanum nigrum*) are prolific and capable of remaining viable in the soil for several decades. Germination flushes may occur under ideal conditions, for example a cohort of seed being brought close to the soil surface through tillage. Diligent management of the weed seed bank is therefore a critical aspect of IWM.*

Figure 2-3. Diligently applying IWM principles across a number of seasons to deplete the weed seed bank can result in minimal weed impact on vegetable production, and eventual cost and time savings in weed management activity (Location: Gingin, Western Australia).

What is IWM?

IWM involves combining all appropriate weed control options in a coordinated and flexible way to minimise the impact of weeds.

Relying on one or two tried and true methods (such as herbicides and tillage) is less likely to succeed in the longer term. It will eventually select for increased populations of certain weeds that are adapted to that method and which may be particularly difficult to control (e.g. herbicide resistant weeds, see 'Maximising herbicide accessibility and effectiveness', in Part 3 – Methods of integrated weed management in vegetable production).

Integrating a range of approaches and timing them appropriately so that they support each other will reduce selection pressure, and make it less likely that particular weed species will come to dominate the paddock. Successful weed management is more likely to occur as a result.

IWM also involves 'knowing your enemy'. Information about when the weed starts to emerge, how quickly it progresses through its various growth stages and when it begins to set seed is critical to planning your IWM approach. What field and weather conditions make it more or less problematic, and how effective various weeding options have been in the past will also provide useful insights for IWM planning.

The key to IWM on vegetable farms is to have a planned strategy that links methods used in a sensible sequence, and the persistence to ensure that each step is diligently carried out.

The success of an IWM strategy cannot be judged on the results of a single cropping season, since it can take several years to reduce the soil weed seed bank depending on the species you are attempting to manage. This means that it may take up to several years of diligent application to begin to reap rewards.

In the longer term, IWM may contribute to improved enterprise flexibility, where cash crops may eventually be grown at any stage of the viable production period without concern that this will result in a vast increase in weed numbers, or that the weed burden will impact too significantly on the cash crop.

"Integrated weed management has been defined as 'a sustainable management system that combines all appropriate weed control options."

The three dimensions of successful IWM

Deliberation

Plan your approach to ensure effective IWM. Take into account available equipment, time, skills and funds; the characteristics of your crops; and the characteristics of the weed species that cause the most problems on your farm.

Diversity

Utilise an appropriate number of weed control methods that target your problem weed species at different stages in their life cycle. The most suitable techniques are likely to vary depending on farm circumstances, but a more diverse approach will improve your chance of success and the sustainability of your IWM strategy.

Dedication

Be persistent with your IWM strategy. You may not achieve immediate results, and it may take several seasons before IWM begins to have a beneficial impact on the weed burden on your farm by reducing the soil weed seed bank. Dedication also means following your planned approach as closely as possible, while also being prepared to modify your approach in response to new recommendations that suggest particular aspects of your strategy can be improved further.

Why is IWM important?

- There is a limited range of registered *herbicides* available to vegetable growers, making over-reliance on herbicides problematic, and potentially increasing the risk of herbicide resistance developing. IWM can significantly reduce grower reliance on herbicides, by making sure several overlapping weed management methods contribute to successful control.
- The various concerns about long-term viability of *plastic mulch films* may mean that IWM approaches which reduce reliance on these products to suppress weeds need to be considered in the near future (see 'Plastic mulch films', in Part 3 – Methods of integrated weed management in vegetable production).
- *Chemical fumigation* is also becoming a less acceptable farm management option over time due to its environmental and potential human health impacts, and alternative approaches are more likely to be required to manage the soil weed seed bank (see 'Chemical fumigation', in Part 3 – Methods of integrated weed management in vegetable production).
- *Annual broadleaf weeds* rely on rapid turnover of large numbers in the weed seed bank to maintain high populations. A well implemented IWM strategy focusing on minimising weed seed production can be expected to result in a relatively sharp decline in their numbers over time.

Case studies have been published to illustrate different ways in which an IWM strategy may be implemented successfully, and the important benefits IWM can provide on vegetable farms.

These case studies offer a range of principles that are relevant to all vegetable growers.

* Diligent hand weeding ultimately pays off.

* Managing weed seed banks through stale seed beds and inter-row cultivation.

Seed bank management

IWM is largely about *soil weed seed bank management*. If the weed seed bank can be reduced over time, weeds will become less of a burden.

Weeds should be targeted at various stages in their life cycle:

- stimulating and then controlling germinating weeds;
- controlling more mature weeds before they produce seed; and
- stopping viable seeds from being added to the seed bank where possible.

Different approaches to IWM will suit different vegetable farms. The best approach may include combining different weed control methods, using them in a particular sequence, or using them at particular time/s in the annual production cycle.

Patience and *diligence* are essential to effective management/reduction of the weed seed bank.

It can take several seasons to have a noticeable impact on the weed seed bank after commencing and sticking with an effective IWM strategy.

Ongoing diligence will ensure that the relatively few remaining weeds are less likely to produce seed, and to create problems in future seasons.

Even though an innovative IWM strategy may be more costly to implement initially, the long-term financial benefits have been demonstrated by Australian research.

One major goal of IWM is to deplete the soil weed seed bank.

Advantages of IWM

- Minimising the possibility of weed control failure.
- Reducing the impact of weed management activities on the environment (most notably by minimising grower reliance on herbicide use).
- Ensuring that the mix of methods used will remain viable into the future.
- Growers who have decided to focus on IWM have discovered that increases in cost, complexity and management inputs are not as great as initially expected.
- Where IWM imposes an extra cost, this is expected to be a short-term issue only, with additional resources and staff time likely to be required. However, IWM will be cost-effective in the longer-term, as the reduced weed burden requires fewer resources to manage, and allows increased crop yield and quality.
- Many IWM-related operations have other farm and crop benefits, beyond weed control.

The challenges of IWM

- Uncertainty regarding its economic benefits.
- Uncertainty about the significance of herbicide resistance.
- A belief that a 'traditional' approach using herbicides and tillage is more effective than a more complex approach integrating other techniques.
- Concern that an IWM approach will be more complex and time-consuming.
- An expectation that new options with conventional approaches are likely to become available (such as new herbicide chemistry).

What is the Goal?

Any IWM strategy in vegetable production should focus on the following broad objectives, targeting weeds at various stages in their life cycle:

1. deplete weed seed bank and stop emergence;
2. suppress or kill weeds;
3. stop seed set;
4. prevent weed seed addition to the soil; and
5. prevent weed seed spread.

However, the mix of IWM approaches that may be relevant to your farm can depend on the severity of the weed infestation. These are detailed in the pages below, and represented by three scenarios of infestation severity.

For all scenarios of weed infestation severity discussed in the following pages, not all methods will be relevant on all farms or in all crops. At the same time, weed control methods not mentioned in the following pages may still be relevant depending on the severity of infestation.

Scenario 1: New or small isolated infestations

Eradication of weeds (reducing the population to zero) is rarely achievable, though it may be feasible where a new weed species infestation has been detected very early when it is still relatively small and restricted in area on the farm, and where it is possible to control weeds before they are capable of reproducing.

Aims

Eradication from the site. Control all plants regularly and before seed is produced to prevent reinfestation in subsequent seasons. Eventually drive the weed seed bank of the new or isolated infestation down to zero. Continue to monitor for potential re-incursion.

Most relevant methods

- Herbicide (including pre- and post-plant/emergent, inter-row and non-selective spot-spraying where crop damage can be avoided); or selective thermal weeding on organic farms.
- Tillage (fallow and pre-plant, inter-row, as well as stale and false seed beds).
- Cover crops and crop competition (to suppress growth through competition; within-crop spot-control still likely to be required to prevent weeds producing seed).
- Regular and diligent hand weeding (before seed is produced).
- Plastic mulch (crop-dependent).
- Soil solarisation may be considered if the patch of weeds covers a relatively small area.
- Farm hygiene: ensure all weeds in adjacent non-cropping areas are controlled before seed is produced; prevent re-incursion through vehicle and equipment wash-down.
- Crop rotation to allow for herbicide rotation and disrupting weed lifecycles.
- Paddock history and planning – produce a weed map showing where the infestation is and its severity to allow regular follow-up control.

Scenario 2: Light widespread infestation

The goal for most vegetable growers is unlikely to be eradication of weeds but rather to reduce their population to a level that has minimal impact on vegetable production. Continued diligence in application of IWM will be critical to ensure that weeds do not become a large problem.

Aims

Maintain low population numbers to restrict build-up of weed seed numbers in the soil. Focus on larger infestations. Prevent or minimise weed seed production and spread.

Most relevant methods

- Herbicide (pre- and post-plant/emergent, inter-row before weeds produce seed, non-selective paddock-wide during fallow/post-harvest to maintain infestation at light level).
- Tillage (fallow and pre-plant, inter-row, as well as stale and false seed beds. Inversion tillage less effective).
- Cover crops and crop competition (to suppress growth through competition).
- Regular and diligent hand weeding (before seed is produced).
- Plastic mulch (crop-dependent).
- Farm hygiene: ensure all weeds in adjacent non-cropping areas are controlled before seed is produced.
- Crop rotation to allow for herbicide rotation and disrupting weed lifecycles.

Scenario 3: Heavy infestation

Vegetable growers may be faced with a severe infestation of weeds having a large impact on crop management and yield. This may occur on land that has only recently been established as a vegetable farm, or a farm where weeds have often gotten out of control. Diligent application of IWM over several seasons, and greater initial effort, can reduce this weed burden to a point where weeds are still present in the crop, but are manageable and are not greatly reducing crop yield (equivalent to Scenario 2).

Aims

Reduce the population to a manageable level that has minimal impact on vegetable production in the longer term (aiming to achieve infestation severity Scenario 2, Light widespread infestation).

Most relevant methods

- Herbicide (pre- and post-plant/emergent, inter-row before weeds produce seed, non-selective paddock-wide during fallow/post-harvest to reduce weed seed bank; be aware of potential for herbicide resistance). Fumigation in the case of very severe infestations.
- Tillage (fallow and pre-plant, inter-row, as well as stale and false seed beds. Inversion tillage may be considered for short term control, especially in very heavy infestations).
- Cover crops and crop competition (to suppress growth through competition; management within the cover crop still likely to be required).
- Hand weeding to control remaining plants before seed produced.
- Crop rotation to allow for herbicide rotation, disrupting weed lifecycles and growing short-season crops to maintain some cash flow.
- Plastic mulch (crop-dependent).
- Farm hygiene: ensure all weeds in adjacent non-cropping areas are controlled before seed is produced).
- Fallow periods to allow for non-selective herbicide application and/or stale/false seed bed to deplete the weed seed bank (see both above).
- Non-selective steam weeding during non-crop period to manage the weed seed bank (where herbicide options are not available or desirable, e.g. on an organic farm or where significant herbicide resistance has been identified).
- Paddock history and planning – weed mapping to record approximate severity of infestation by area and to plan management activities.

Overview of Methods used in IWM

There is no 'one size fits all' IWM strategy for vegetable production. Every farm is likely to require a different approach. This is due to:

- the great variety of crop types (from smaller stature leafy vegetables through to tall stature corn);
- the variety of weeds (ranging from grass weeds through to heavily seeding broadleaf species or persistent weeds such as nutgrass) and the severity of weed outbreaks;
- climate and soil variation in different vegetable production regions of Australia; and
- available resources, skills and time to implement different methods.

Things to consider when deciding which methods to include in your IWM strategy include the following.

- Time of year and growing season of the vegetable crop.
- The stage in the life-cycle of the vegetable crop when weed management options are required (including the fallow).
- The weed species present and/or dominant in the paddock (please refer to the various guides to 'Priority weed species and their management' for further information).
- The type/s of vegetable crops being grown.
- Experience in using different methods.
- Available resources to implement different methods (funds, staff, equipment and time).

In Part 3, 'Methods of integrated weed management in vegetable production', we provide further detail on the various methods that vegetable farmers may consider including in their IWM strategy.

Please refer to relevant sections of Part 3 for further details on each of the weed control methods introduced here.

Tillage, herbicides and stale/false seed beds

Repeated tillage and *selective or non-selective herbicides* are commonly used together to reduce the population of the most important weed species before each crop planting.

Using a *stale or false seed bed* involves encouraging weed seeds to germinate within formed crop beds and then controlling the seedlings either through herbicide application or light tillage. Doing this before plants set seed can reduce the soil weed seed bank in the longer term. *Thermal weed control* (steam or flame weeding) may also be used to manage recently germinated weeds in a stale or false seed bed.

Inter-row tillage is a useful option within growing crops, and is usually undertaken using specialised equipment and to a shallow depth only, to manage recently germinated weeds. It will be most relevant during early stages in the crop life cycle, once the crop has established and can survive the tillage operation, but before the canopy closes or the crop root and plant structure may be damaged by this precision activity.

Figure 2-4. Repeated tillage prior to crop planting can be used to reduce the soil weed seed bank. When used alongside herbicides as part of a stale or false seed bed approach to encourage weed germination and then control these weeds, reduced weed germination within the crop can be expected (Location: Myalup, Western Australia).

Hand weeding

Hand weeding nearly always has a role to play in successful IWM, often as a follow-up to control remaining weeds missed through other weed management activity, or in locations where other methods cannot be used (such as directly next to crop plants).

Diligent hand weeding, integrated with other methods, has proven successful on Australian farms in reducing the weed seed bank by ensuring that few new seeds are deposited in the soil. Several years of dedication will be necessary in order to succeed.

Figure 2-5. Hand weeding can be used successfully to follow up on survivors of other weed management activities (Location: Gatton, Queensland).

Crop rotation, cover cropping and fallow management

Growing the same crop continuously, or using the same crop cycle each year, can eventually allow certain weeds to become common, and potentially dominant.

Including a *different cash crop* (for example a non-vegetable crop) or a *green manure or biofumigant cover crop* during the traditional non-cash crop period in the rotation may allow use of *selective herbicide*. For example, some vegetable growers in the Bundaberg region in Queensland grow sugar cane in their vegetable fields outside the vegetable growing season, giving them access to a much wider spectrum of herbicides to manage broadleaf weed species. Some vegetable growers also choose to grow a winter cover crop using a grass species, opening up the possibility of using similar broadleaf-specific herbicides.

Changing the annual crop rotation to include different vegetable crops can provide similar benefits. It can break the growth cycle of dominant weeds by making more diverse weed management practices available to 'keep the weeds guessing'.

Fewer weeds may be expected to appear in a fallow paddock when a cover crop is grown, especially when it produces a dense canopy which helps to suppress weeds.

Including a fallow period in the crop rotation may also allow non-selective herbicide application to be used to reduce the weed seed bank, by ensuring that all weeds are killed before seed set. This is also the best time to consider implementing a *stale or false seed bed*, to deplete the weed seed bank.

Figure 2-6. Cereal rye (Secale cereale) *has proven to be an effective winter cover crop option for weed suppression in industry field trials in Western Australia (Location: Myalup, Western Australia).*

Farm hygiene

Implementing and diligently adhering to a farm hygiene program will help to limit weed seeds finding their way onto farms (or between heavily infested and relatively uninfested paddocks).

The overall objective is to reduce the risk of viable weed seed being added to the seed bank, by managing on-farm traffic and other vectors for weed seed importation, as well as minimising weed seed production on the paddocks and their immediate surroundings.

Figure 2-7. Establishing a fixed equipment wash-down bay can help restrict the spread of weed seed (Location: Richmond, Tasmania).

Plastic mulches

Plastic mulch is economically viable in some high value crops. It forms a key component of IWM in these crops by directly suppressing weed growth within the crop beds, and provides a range of other benefits (e.g. soil moisture retention). Plastic films can also be used to carry out soil solarisation with increased temperatures to somewhat deplete the weed seed bank near the surface.

However, plastic films face an uncertain future due to rising disposal costs and environmental impact concerns.

Figure 2-8. Plastic mulch films are used in both warm and cool climate vegetable production in Australia (Location: Moriarty, Tasmania).

Crop agronomy and management

Close plant spacings, competitive crop varieties, optimal fertiliser and irrigation use to encourage crop vigour, and in-crop spraying of selective herbicides (where registered), can result in low survival of weeds in the vegetable crop. A similar policy may be pursued in cover crop rotations.

Using a drip irrigation system can mean that the non-irrigated inter-rows remain dry (unless rain falls) throughout most of the growing period, with consequent reductions in weed population in the inter-row space.

Paddock and farm planning

Plans to minimise weed growth within cash crops may potentially include shifting most cash crop production to the parts of the farm where the weed infestation is lower; or avoiding planting vegetables on land that is known to have a history of heavy weed infestation.

IWM should start before the first crop is planted: on new land, it is advisable to grow vegetable crops only after at least two seasons of effective weed management. This will help reduce the weed seed bank to a more manageable level. Using a range of complementary methods from those described above will maximise early success.

Timing of IWM Activities

The critical period of weed control

The critical period of weed control on vegetable farms is that period from before the crop has been sown or transplanted to before it produces a canopy that can out-compete late-germinating weeds. Managing weeds during the critical period will ensure that weed impact on final crop yield is minimised. The critical period can vary depending on the crop being grown and time to canopy closure, as well as planting method, planting density, soil moisture and temperature, planting season, crop variety chosen, weed species present at the site, and weed density.

Stages of weed control in the crop cycle

Effective weed control at stages in the crop cycle other than at the 'critical period' may also contribute to successful IWM and a healthy vegetable crop. The aim of controlling weeds at each stage may be as follows.

1. Pre planting: controlling weeds to provide a uniformly clean seed bed and facilitate establishment of the cash crop (including stimulating and managing recently germinating weeds to reduce the seed bank). Relevant methods may include repeated tillage, selective or non-selective herbicides or thermal weed control, all of which may be used as part of a stale or false seed bed.
2. Early crop cycle: controlling recently germinated small weeds within the crop beds to reduce competition before the crop canopy closes. Relevant methods may include selective herbicides, inter-row tillage and hand weeding.
3. Late crop cycle: removing larger weeds in more mature crops before harvest, to minimise replenishment of the soil weed seed bank. Hand weeding will be the most relevant method at this stage.
4. Post-harvest: crop residue incorporation and cleaning up the crop beds after harvest and during the fallow to avoid weed seed production and preserve soil moisture and nutrients for following crops. Relevant methods will include non-selective herbicides and tillage.

Emerging IWM Technologies

At the time of writing, several technologies were under development or starting to be used in the vegetable industry. Some examples include:

- Robotic weeding using advanced sensing equipment, which can be used for precision control of weeds in fallow paddocks or within a growing crop, via targeted herbicide application or tillage;
- Microwave weed management, which provides a non-chemical approach to managing intractable weeds as well as the weed seed bank residing in the soil; and
- Drones, which can be used to map and monitor weed problems in vegetable fields, as well as provide targeted herbicide application to areas of the farm, such as irrigation lines, that cannot be accessed easily by machinery.

Figure 2-9. The Digital Farmhand, developed in Australia by Agerris, is one of several robotic systems under development for automated completion of a variety of farm management activities, including precision weed management (Location: Richmond, New South Wales).

These and other technologies offer the potential to transform IWM as well as monitoring and management of the whole farming system. Weed management in fallow paddocks, non-crop areas and within crops themselves may be improved significantly. At the same time, vegetable growers may be able to rely less on current methods such as hand weeding, broad-scale herbicide application, and frequent cultivation. Broader farming systems benefits may include:

- Improved timeliness and diverse, synchronous activities (e.g. spraying and tillage), leading to better efficacy of operation and inputs;
- Continuous monitoring and action, enabling farmers to predict or anticipate problems;
- Information about multiple farm features can be collected, e.g. pests and disease, and soil conditions (moisture, nutrient status);
- Information is recorded using GPS technology, so the specific location of every detection and every resulting action is captured;
- All the data collected creates a rich historical record ('Big Data') of weeds, pests, soil health, yield, climate, and farming practices carried out; and
- Decision support systems enable more automation of farming, well-informed planning of crop rotations, and the reallocation of labour and other resources.

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v 1.0; May 2021.

Hort Innovation Strategic levy investment | VEGETABLE FUND

This project has been funded by Hort Innovation using the vegetable research and development levy and funds from the Australian Government. For more information on the fund and strategic levy investment visit horticulture.com.au

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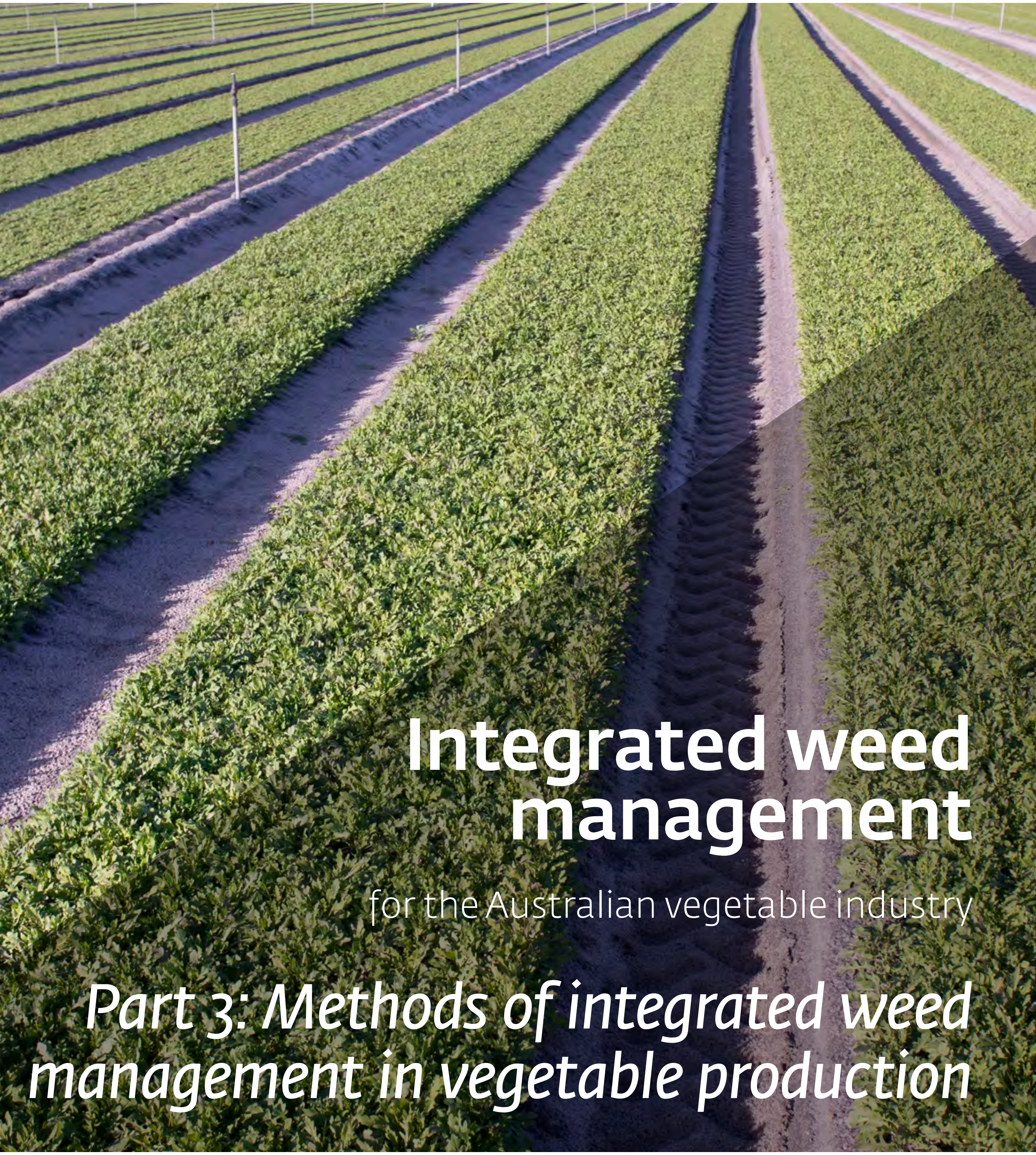

Integrated weed management

for the Australian vegetable industry

Part 3: Methods of integrated weed management in vegetable production

Hort Innovation
Strategic levy investment

VEGETABLE FUND

une
University of New England

Disclaimer

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Strategic levy investment

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This project has been funded by Hort Innovation using the vegetable research and development levy and funds from the Australian Government. For more information on the fund and strategic levy investment visit horticulture.com.au

Table of Contents: Part 3

Components of IWM in vegetable production

In this manual we have categorised each of the management techniques as follows:

Preventive methods: implemented before the cash crop is established (planted or sown), in order to reduce weed emergence within the crop beds.

Direct physical methods: implemented directly within the crop beds after the crop has been established, generally in order to control selected weed plants that may have an impact on crop yield or quality, or on management of the crop.

Cultural methods: a range of agronomic practices are available to improve the capacity of the crop to out-compete weeds.

The remainder of Part 3 includes a detailed discussion of the various weed control methods. We also include key references that will provide you with more information on each method.

These weed control methods may be used together in various ways depending on skills and resources available, crop rotation plan, weed burden and weed management objectives. IWM is outlined in Part 2 of this Manual, 'The principles'.

Summary: managing weeds on vegetable farms

There are a range of methods available to manage weeds in vegetable production, however each is suited to different stages of the weed and/or crop life cycle.

There are relatively few registered herbicide options for use within many vegetable crops, particularly once the crop is actively growing.

Preventive weed management methods are implemented before the cash crop is planted or sown in order to reduce weed emergence within the crop beds. They may include: pre-plant residual herbicide; post-plant and post-emergence selective herbicide; fallow or pre-plant tillage; stale and false seed beds; plastic and biodegradable mulches; weed management in non-cropping areas of the farm; farm hygiene; and soil solarisation.

Direct physical weed management methods are implemented directly within the crop beds after the crop has been established, generally in order to control selected weed plants that may have an impact on crop yield or quality, or on management of the crop. They may include: selective herbicide application either within crop beds or directly adjacent; hand weeding; inter-row tillage; controlled traffic farming; and steam or flame weeding.

Cultural weed management methods include a range of agronomic practices utilised to improve the capacity of the crop to out-compete weeds, for example: green manure and biofumigant cover crops; cash crop and variety selection; cash or cover crop sowing rate; row spacing and orientation, and irrigation strategy adjustments.

The key to effective management of weeds in vegetable crops is to integrate a number of effective methods from this selection into a strategy. This approach is known as Integrated Weed Management (IWM). The selection of methods to include in IWM will depend on the crops grown, weed species present, and a variety of farm management, resourcing and economic factors.

While immediate weed control is normally imperative, the overarching goal of IWM is to reduce the weed seed bank in the soil over time, ideally by integrating methods which seek to manage weeds at different stages of their life cycle.

The critical factors for weed control success using IWM include:

- Identifying and rigorously implementing those particular methods which have been shown to have the greatest benefit on reducing the weed burden on a particular farm.
- Appropriately timed implementation of particular weed control methods, with consideration of the weather, weed life stage, crop life cycle stage, and ground conditions.
- Diligently adhering to the best available IWM strategy in order to ensure that where possible, weeds are removed from crop beds before they have a chance to set seed.
- Developing a detailed knowledge of the weeds found on the farm, their key characteristics, and how to manage them with greatest benefit.
- Conducting whole farm planning with regards to weed management, including flexibility in approach to take changing circumstances into account.

Part 3A: Chemical weed management

Herbicides (and to a much lesser extent chemical fumigants) are a mainstay of weed control in vegetable crops. Here, we summarise several options:

- **Pre-plant or pre-emergent herbicides** can be used to control a relatively wide range of weeds, and have a residual control effect.
- **Selective herbicides** used to manage weeds within growing vegetable crops, either post-plant or post-emergence.
- **Non-selective herbicides** used to control all weeds in the paddock, immediately after harvest, during fallow periods, or used in a targeted way to control specific weed outbreaks, or in adjacent non-cropping areas such as wheel tracks, headlands or irrigation lines.
- **Chemical fumigation**, used to manage soil pests but also known to have some effect on weed seed.

Minor use permits provide the industry with access to additional herbicide options, but overall there are relatively few registered herbicides available for many vegetable crops, especially for selective broadleaf weed control in growing crops.

Given the few registered herbicides available, herbicide resistance may be an increasingly important issue for vegetable growers. In the pages below, more information is provide on approaches to minimise the chance of herbicide resistance developing on your farm, and to manage outbreaks of resistant weed species.

Please refer closely to the herbicide label for directions, and consult your agronomist if you are unsure.

Pre-plant/pre-emergent residual herbicides

Pre-plant and pre-emergent herbicides ('residual herbicides') generally control a wide range of weed species, and are used before crop planting or crop emergence. They are designed to provide some continued control of weeds germinating in the early period of crop growth, through residues present on the soil surface.

They offer an alternative to more extensive postharvest tillage in the previous crop, fallow tillage, and use of non-selective herbicides during the fallow, but they can also be used to support those approaches for more effective weed management.

Figure 3-1. Applying pendimethalin (Stomp®440) pre-plant to transplanted lettuce beds near Gatton, Qld. Pendimethalin is an effective and commonly used pre-emergent residual herbicide, but can stunt lettuce crop growth under certain conditions. Label directions for application (for example rate, timing and climate and soil conditions) should always be followed closely to minimise this risk.

Advantages

Residual herbicides usually **persist** on the soil surface for a period of time after application (up to several months), controlling successive weed germinations. Their ability to persist in the soil can vary depending on application rate, soil type (texture, pH, organic matter), rainfall or irrigation, temperature and the herbicide's characteristics.

Both pre-plant and pre-emergent residual herbicides can be a significant expense for growers, but will be more **cost-effective** than alternatives such as much more extensive hand weeding during later stages of the crop.

Disadvantages

Some crop **damage** is possible with residual herbicides under certain circumstances, for example:

- Lettuce or brassica crop stunting under certain conditions when residual herbicides are applied at maximum recommended rates.
- Brassica crop damage resulting from residual herbicide use in waterlogged soils, or very cold weather conditions.

Longer residual and plant-back periods (of up to twelve months depending on herbicide and crop) can make it difficult for growers to consider some pre-plant and pre-emergent herbicide options within their annual crop cycle.

Despite this, Australian vegetable growers have usually noted that their crops are not adversely impacted by residual herbicide application, providing they follow guidelines appropriately.

Timing

Timing of application depends on herbicide and crop, but is likely to be before transplant or crop emergence, or within a day of crop transplant into the crop beds (e.g. Figure 3-1). Herbicide labels will provide specific timing recommendations for each crop.

Timing is critical for effective control of weeds with residual herbicide, since appropriately timed applications will allow the crop plants to more effectively out-compete later germinating weeds.

Timing is also likely to involve factors such as bed preparation, soil moisture content and weather, and the ability to apply the herbicide and then avoid bed traffic. This means that pre-emergent or pre-plant herbicide application must be coordinated with overall management of bed preparation and crop planting.

How to use

Residual herbicides are generally applied to beds that have been formed for transplanting, or in which crop seeds are about to germinate (e.g. Figure 3-1). They are usually incorporated into the soil with a light till, or by irrigation or rainfall. Soil disturbance should be avoided once the residual herbicide has been applied to maximise its effectiveness.

Please refer closely to the herbicide label for directions, and consult your agronomist if you are unsure.

Other considerations

Choice of residual herbicide will depend on the weed species causing difficulty, plant-back periods for following crops, and the types of herbicides used previously.

Herbicide rotation is recommended where possible to avoid weed resistance to commonly used herbicides.

Integration with other techniques

Techniques that may *immediately precede* residual herbicide application can include **tillage** during bed formation, and **stale or false seed beds** to reduce the weed seed bank within the formed beds.

Techniques to *immediately follow* residual herbicide application should not be considered while the residual herbicide blanket is in effect. But they may include selective **hand weeding** within the crop beds, or targeted **inter-row tillage** before the crop canopy has closed.

Integration with other techniques will depend on farm circumstances (crops, soil and climate, staff, budget, and timing within crop cycle).

Maximising success

Growers should take these issues into account to maximise the effectiveness of residual herbicides:

- **Soil moisture:** soils must be moist for pre-plant and pre-emergent residual herbicides to be most effective. Growers have found these herbicides to be less effective during extended dry weather spells.
- **Usage rate:** it may be tempting to reduce the application rate when using residual herbicides to reduce costs, or to reduce the risk of crop damage. However, recommended rates as displayed on the label should always be used, since applying at reduced rates makes the herbicide less effective than expected. Relying on lower rates also increases the risk of **herbicide resistance** developing on your farm.
- **Maintaining the herbicide blanket:** following application, minimal soil disturbance is desirable for as long as possible to maintain an effective residual 'herbicide blanket' on the soil surface. Herbicide labels will provide more details on the length of time that minimal soil disturbance is desirable.

Key references and further reading

Cotton Research and Development Corporation. 2013. WEEDpak: a guide to integrated weed management in cotton. Narrabri: Cotton Research and Development Corporation.

Preston, A.L. (Ed). 2019. Integrated weed management in Australian cropping systems. Grains Research and Development Corporation.

Post-emergence and post-plant selective herbicides

Once the crop has germinated or has been transplanted, herbicide management within the crop will reply on a limited range of post-emergence and post-plant herbicides ('selective herbicides'). These will kill a selected range of weeds while allowing the crop to survive.

Selective herbicides are an effective alternative to inter-row weed management activities such as precision tillage, hand weeding or selective thermal weeding, however using these methods together is likely to achieve the best results.

Advantages

Availability of selective herbicides for **grass** control in many vegetable crops means that grass ('monocotyledon') weeds are rarely a significant issue in conventional vegetable production (e.g. Figure 3-2).

Where they are available for certain crop and **broadleaf** ('dicotyledon') weed combinations, selective herbicides are critical to an effective IWM strategy. They can significantly reduce the need to use other more expensive and time-consuming weed management methods, such as hand weeding and selective tillage.

Figure 3-2. Available of a range of selective herbicides means that grass weeds are rarely a significant issue on vegetable farms (Location: Fleurieu Peninsula, South Australia).

Disadvantages

While grass weeds are generally controlled with selective herbicides, **not all grass species may be managed with selective herbicides** once the crop is growing.

You should also remain aware of the potential for **herbicide resistance** to develop, as a result of over-reliance on a limited range of selective products. For example, populations of annual ryegrass (*Lolium rigidum*) are already resistant to a number of herbicide modes of action, and resistant populations have been noted in Tasmanian vegetable production (see also 'Herbicide resistance').

Selective herbicides are of relatively limited use in managing broadleaf weeds within broadleaf vegetable crops. At the time of writing, their availability was limited to selected vegetable crops such as cucurbits, brassicas, onions and carrots, and a limited range of broadleaf weeds. It is likely you will need to rely on other management tactics to control broadleaf weeds once the crop is growing.

Timing

Selective herbicides are most often registered for selective control of grass weed species in a limited number of broadleaf vegetable crops. A limited number of options are also available to manage a small number of broadleaf weeds in some vegetable crops.

Selective herbicides are usually used relatively early in the crop life cycle, when weeds have just germinated and before the crop forms a canopy.

Timing is as affected by soil moisture content and weather, and ability drive machinery onto the paddock to apply herbicide.

How to use

Selective herbicides require weeds to have germinated, and work via **foliar application** (application to plant leaves), being absorbed by weeds through leaves and stems.

Specific directions for usage vary depending on the crop and weed species in question, and registration requirements may vary between states.

Please refer closely to the herbicide label for directions, and consult your agronomist if you are unsure.

Other considerations

It is worth checking with your supplier to determine the current range of available selective herbicides to use within growing vegetable crops, including availability of products for different crops, and weeds controlled.

Please consult the list of minor use permits for herbicides (available from the AVPMA), in case other short-term options are available (see 'Minor use permits').

Selective herbicides can be particularly effective when available and used in crops that have a longer growing period (for example, onion crops which can take up to six months to grow, or winter lettuce crops in southern Australia). The longer the crop is in the ground, the greater the opportunity for weeds to grow and produce seed, and to become an even more significant issue in the next season. Controlling these weeds with herbicide before they have a chance to produce seed will have a lasting effect on the weed seed bank.

Herbicide rotation is important to avoid weed resistance to commonly used herbicides.

Integration with other techniques

Techniques that may *immediately precede* residual herbicide application might include **tillage** during bed formation, **stale or false seed beds** to reduce the weed seed bank within the formed beds, and application of a **pre-emergent herbicide** if registered for your crop.

Techniques to *immediately follow* selective herbicide application may include selective **hand weeding** within the crop beds to remove remaining weeds, **inter-row tillage**, or potentially selective **thermal weeding** (steam or flame weeding).

Integration with other techniques will depend on farm circumstances (crops, soil and climate, staff, budget, and timing within crop cycle).

Maximising success

The effectiveness of foliar-applied selective herbicides will also be affected by a range of factors. These apply whether grass or broadleaf weed species are being targeted.

Each of these issues is likely to be covered on the herbicide label if relevant, while your supplier or agronomist may also be able to provide specific advice:

- **The level of weed stress.** Weeds that are stressed due to lack of moisture, nutrient deficiencies, disease and pest pressure, or temperature extremes are likely to be less susceptible to herbicide control. Wetting agents may improve the performance of herbicides where weeds are suffering from moisture stress. Herbicide labels should be consulted to make sure appropriate additives are being used.
- **Application considerations** such as droplet size and equipment, and weather conditions, such as windy conditions which may cause spray drift.
- Some selective herbicides may cause crop **stunting or damage**. This is likely to be associated with application rates and conditions, so that label recommendations should be followed exactly.
- **Time of application**. A general rule is that younger seedling weeds will be controlled more effectively by selective herbicides than more mature plants, but refer to the herbicide label for specific recommendations.
- If applicable, the **withholding period** will be available on the herbicide label. Some selective herbicides may have potential effects on following crops if planted too early after herbicide application.

Key references and further reading

Cotton Research and Development Corporation. 2013. WEEDpak: a guide to integrated weed management in cotton. Narrabri: Cotton Research and Development Corporation.

Preston, A.L. (Ed). 2019. Integrated weed management in Australian cropping systems. Grains Research and Development Corporation.

Fallow and postharvest herbicides

Foliar-applied **non-selective** herbicides (sometimes also known as broad-spectrum or knockdown herbicides) may be used to control weeds during fallow periods in the annual cycle, as well as weeds that have grown within the crop and remain after harvesting.

The best-known non-selective herbicide is glyphosate, which is widely used at the time of writing due to its affordability, ease of use and flexibility. However, there are a number of other options available including paraquat, Spray.Seed® (paraquat/diquat), and glufosinate.

Vegetable farms on which a fallow is included as part of the annual crop rotation often have a larger soil weed seed bank. This suggests that diligent management during the fallow to restrict weed seed production will be critical in reducing the overall burden of weeds in the longer term.

Non-selective herbicides may be used in the postharvest and fallow periods as an alternative to more regular tillage, and this approach is likely to be more cost-effective and beneficial to soil health. Using these two approaches together, though, is likely to achieve the best results. Selective herbicides may be considered in preference to non-selective herbicides during the fallow and postharvest periods, where they are more effective for particular weeds.

Figure 3-3. Fallow paddocks such as this one near Darwin, Northern Territory, can be an important weed refuges if careful fallow management (such as herbicide application, tillage or potentially slashing) is not undertaken.

Advantages

Non-selective herbicides used after harvest or during fallow periods are one of the most effective weed control tactics available.

- Approximately **95% weed control** is possible when non-selective herbicides are used in ideal conditions.
- Application is significantly quicker than cultivation, resulting in considerable **savings in labour and fuel**.
- Non-selective herbicides are also **relatively affordable to purchase**.
- Non-selective herbicides are also **non-residual**, quickly become deactivated when coming into contact with the soil.
- They are a critical part of **farm hygiene** management on your vegetable farm by allowing effective suppression of weeds within fallow fields (see 'Farm hygiene').

Disadvantages

- As with selective herbicides foliar-applied non-selective herbicides are **less effective when weeds are stressed**. Where weeds are likely to remain stressed during the fallow period, growers may wish to consider alternatives such as tillage.
- In some vegetable production regions in Australia, **year-round production** means that fallow periods are rarely present in the annual production cycle, and non-selective herbicide application is not particularly relevant.
- Elsewhere, **weather conditions** may preclude non-selective herbicide use during a fallow period. The most notable example is the northern Australian wet season, which makes any on-farm.
- You should always be aware of the potential for **herbicide resistant weed populations** to emerge on your farm, particularly if non-selective herbicides are heavily relied upon. Glyphosate resistance is discussed further in 'Herbicide resistance', and appears to be growing in significance.

Timing

Non-selective herbicides are formulated to kill all or most plants they come into contact with, so are not appropriate for use within a crop.

Timing is likely to involve factors such as soil moisture content and weather, ability drive machinery onto the paddock to apply herbicide, and planned activities such as postharvest or fallow tillage operations. This means that non-selective herbicide application should be coordinated with overall paddock management in non-cropping periods.

How to use

Specific directions for usage are likely to vary depending on the crop and weed species in question, and registration requirements may vary between states.

Please refer closely to the herbicide label for directions, and consult your supplier or agronomist if you are unsure.

Other considerations

Herbicide rotation is recommended where possible to avoid weed resistance to commonly used herbicides. Where herbicide resistance is a cause for concern, selective herbicides may be appropriate to use postharvest or during a fallow period.

Integration with other techniques

Techniques to *immediately precede* fallow and postharvest herbicide application may include those used within a crop, such as **selective herbicide** (if registered for your crop), selective **hand weeding** within the crop beds to remove remaining weeds, **inter-row tillage**, or potentially selective **thermal weeding** (steam or flame weeding).

Techniques that may immediately follow fallow and postharvest herbicide application will include those used to prepare for the next crop, such as **tillage** during bed formation, **stale or false seed beds** to reduce the weed seed bank within the formed beds, and application of a **pre-emergent herbicide** if registered for your crop.

Integration with other techniques will depend on farm circumstances (crops, soil and climate, staff, budget, and timing within crop cycle).

Maximising success

Effectiveness of non-selective herbicides can be maximised by closely **following label directions**, including suitable weather and field conditions, and appropriate rates for the weed species present.

Further gains in non-selective herbicide use can be made further by using a **double knockdown** approach. This refers to using two herbicides with different modes of action (MOA) sequentially, for example, using glyphosate (Group M) followed by paraquat/diquat (Group L).

The second herbicide application will control most survivors of the first application, as well as most additional weeds germinating after the first herbicide application.

Double knockdown herbicide use may require a longer break between crops, and will require an interval of between one and 14 days between applications. Each herbicide should also be applied at the full recommended rate.

By employing two different MOAs, double knockdown can help to reduce or delay the risk of herbicide resistance developing on your farm. The strategy may also be useful in paddocks where herbicide-resistant weed populations are already found, by controlling many of the resistant weeds with the second application of a different MOA product.

Preston (2019) provides further detail on the double knockdown approach.

Key references and further reading

Cotton Research and Development Corporation. 2013. WEEDpak: a guide to integrated weed management in cotton. Narrabri: Cotton Research and Development Corporation.

Preston, A.L. (Ed). 2019. Integrated weed management in Australian cropping systems. Grains Research and Development Corporation.

Herbicide control in specific locations

Where weeds need to be controlled in specific areas adjacent to the crop beds, two options are discussed here for consideration as part of your overall IWM strategy. Both involve careful use of non-selective herbicides.

Shielded application of herbicides normally involves using a non-selective herbicide such as glyphosate, paraquat/diquat or glufosinate to manage weeds in non-crop spaces such as headlands, irrigation lines and channels, the space between crop beds (e.g. wheel tracks), and around other infrastructure (Figures 3-4 to 3-6).

Alternatives to inter-row shielded spraying include: inter-row tillage; hand weeding; reduce moisture in wheel tracks using drip irrigation; and producing a thick crop canopy to out-compete weeds.

Spot spraying dense infestations either within or adjacent to a growing crop with a non-selective may be considered where the weed infestation is particularly dense, or where a difficult to manage weed species (such as nutgrass, *Cyperus rotundus*) is present.

Within the crop bed, spot spraying is unlikely to be feasible due to the risk of crop damage, though technologies are under development which may allow targeted in-crop herbicide application (see 'Robotic weeding'). Lower-risk alternatives may include hand weeding, inter-row tillage, or selective thermal weeding (steam or flame).

Figure 3-4. Irrigation lines controlled for weeds with shielded non-selective herbicide application (Location: Fleurieu Peninsula, South Australia).

Figure 3-5. Customised shielded inter-row herbicide unit (Location: Bundaberg, Queensland).

Figure 3-6. Mankar hand-operated low volume shielded herbicide applicator used with a non-selective herbicide to manage inter-row weeds at a market garden farm (Location: Moriarty, Tasmania).

Advantages

When they are allowed to grow and produce seed, inter-row weeds are an important ongoing source of weed seed. Managing these weeds using **shielded inter-row herbicide application** can be an important aspect of a farm hygiene strategy (see 'Farm hygiene'). It can reduce the risk of weed seed spreading from the inter-row space into crop beds through farm activities (e.g. tillage) or natural methods of spread (e.g. wind).

Outside the crop beds, spot-spraying with non-selective herbicide should be an integral part of integrated weed management on your farm. The objective is to manage weeds before they produce seed around the areas surrounding your vegetable paddocks.

Disadvantages

Even when using a shielded spray unit, there is still some risk of **crop damage**. Some approaches to minimise this risk are discussed below in 'Other considerations and maximising success'.

Tractor-mounted shielded spraying equipment is also most likely to be feasible within crops that have wider spacing between the crop rows (such as cucurbits), than in crops where the inter-row space is only as wide as your tractor's wheel track (such as lettuce or brassicas). However, relatively narrow shielded implements (e.g. Figure 3-6) may be worth consideration.

Similarly, spot-spraying within vegetable crop rows is unlikely to be feasible due to the high risk of crop damage.

Timing

Shielded inter-row herbicide application is relevant when a cash or cover crop is currently growing, there is a weed issue that requires management in the irrigation lines or inter-row spaces, and where the risk of crop damage through spray drift is minimal when using a shielded device.

Spot spraying may be used at any time in the crop and non-crop cycles to control particularly dense infestations, to follow up on other weed management activities to control surviving plants, or to prevent a few weeds setting seed and becoming a more significant outbreak. It may be used within a cash or cover crop, although this is relatively unusual in vegetable production. More likely, it makes an important contribution to control weeds in adjacent non-cropping areas where they are present.

How to use

Inter-row herbicide application is not feasible without a shielded spray unit, which will minimise spray drift and therefore damage to nearby crop plants. Tractor-mounted units are available (or may be customised) for use on large-scale farms (Figure 3-5). Hand-operated units are also available for use on smaller vegetable farms and market gardens (Figure 3-6).

Spot spraying will also require a shielded applicator if being used within a crop bed. If it is being used outside the crop beds (e.g. around headlands, fence lines, sheds and equipment), standard portable spray equipment will be most suitable.

Please refer closely to the herbicide label for directions, and consult your supplier or agronomist if you are unsure.

Other considerations

Some growers are concerned about the potential for non-selective **herbicide resistance** to develop on their farm, while others may have already identified resistant weed populations (see 'Herbicide resistance'). Where this is the case, **selective** herbicides may be appropriate to use postharvest or during a fallow period.

Integration with other techniques

Techniques that may *immediately precede* **non-selective herbicide application** will include all weed management activities within a cash crop, such as **pre-emergent** or **selective herbicides**, **inter-row tillage**, and selective **hand weeding** to control survivors within the crop.

Techniques to *immediately follow* **non-selective herbicide application** may include fallow or bed-preparation **tillage** operations, **cover cropping** to suppress weed growth during an extended non-cash crop period, or **stale or false seed beds** (possibly including a non-selective herbicide application) immediately prior to the next crop.

Spot spraying may be used at any time on adjacent non-cropping areas during a cash crop, cover crop or fallow period, providing sufficient care is taken to avoid spray drift crop damage. It is an integral part of effective **farm hygiene**.

Integration with other techniques will depend on farm circumstances (crops, soil and climate, staff, budget, and timing within crop cycle).

Maximising success

The risk of crop damage due to spray drift when controlling inter-row weeds with **shielded equipment** can be minimised in a number of ways:

- setting up the shielded unit so that it and the spray nozzles are as close to the surface level as possible;
- using wider crop row spacing;
- using larger droplet sizes or low-volume application at high rates;
- completing the activity when there is no breeze; and
- considering hand-operated shielded spray units (Figure 3-6) which may provide the user with greater control over spray drift than tractor-mounted units, but will require more time to cover the same area of the paddock.

It is worth trialling shielded spraying in a small area first, to identify any crop damage risks before using it for whole crops.

Some considerations for effective and lower-risk **spot spraying** may include:

- using a hooded spray wand to avoid spray drift onto nearby crop plants;
- determining whether herbicide residue from the product being used is likely to cause any lasting damage to the current crop;
- ensuring that staff carrying out this activity are thoroughly trained in avoiding unnecessary crop damage; and
- considering whether alternative approaches could just as effectively manage the weed problem, at similar or lower cost and with less risk to the crop.

Key references and further reading

Cotton Research and Development Corporation. 2013. WEEDpak: a guide to integrated weed management in cotton. Narrabri: Cotton Research and Development Corporation.

Preston, A.L. (Ed). 2019. Integrated weed management in Australian cropping systems. Grains Research and Development Corporation.

Chemical fumigation

Fumigating the soil in formed crop beds using a broad spectrum chemical fumigant such as metham-sodium is common practice on some vegetable farms to manage nematodes, diseases, insect pests as well as some weeds.

Advantages

Chemical fumigation is considered to have some effect on weed management by reducing the number of viable seeds in the soil. It can potentially reduce a grower's reliance on herbicides, as well as other weed control methods that may be required within the crop beds once the crop has grown, such as hand weeding.

Disadvantages

Chemical fumigation is not widely used due to a range of social and environmental concerns related to the toxicity, difficulty of use, and cost. Its future availability also seems to be uncertain with some products already phased out of production. Concerns include:

- Concerns over their effects on overall soil health, by impacting beneficial as well as harmful soil organisms.
- Concerns regarding their residual toxicity in both plants (including crops) and soils.
- The complexity of soil treatment using chemical fumigation
- Growing cost of fumigant products, making them uneconomic to use in some vegetable crops.
- Potential for chemical drift, and therefore impact on neighbouring lands.
- Perceptions of neighbours around the health risks of chemical fumigation, related to the known toxicity of fumigant products to both humans and animals.
- Concerns for the health of farm staff using the chemical fumigation.

These significant concerns are likely to see all chemical fumigant products phased out of production or prohibited by legislation in the near future. This suggests that growers should not rely on chemical fumigation as part of their longer-term IWM strategy.

Alternatives

Since chemical fumigation is becoming less socially and environmentally acceptable, it is likely to be phased out of use, attention may be better directed towards other weed management methods. Alternatives may involve any weed management approaches that help reduce the weed seed bank within crop beds – which is the key advantage of chemical fumigation. Alternatives which are considered relatively close to chemical fumigation (because they can be used to destroy viable weed seed) include biofumigation using selected cover crop varieties (see 'Biofumigation and weed management'), and soil solarisation (see 'Soil solarisation').

However, your key objective should be to remove weeds where possible before they produce seed. All of the weed control approaches discussed in this manual contribute to that objective, in various ways.

Maximising herbicide accessibility and effectiveness

Minor use permits

In addition to the various herbicides currently registered for use across vegetable production in Australia, the Australian Pesticides and Veterinary Medicines Authority (APVMA) maintains a minor use permit system.

This allows for short-term legal use of herbicides where the product is not currently registered for that use. The system allows vegetable growers access to different herbicides in their crops.

It is possible for growers to work with Hort Innovation Australia, their agronomist and/or neighbours to obtain a minor use permit, if they believe this would be beneficial. Hort Innovation will work with the APVMA, who will make the final determination regarding the permit.

Growers must agree to comply with permit conditions imposed by the APVMA, or the permit will not be issued. The APVMA will make its final determination based on factors such as crop safety, environmental and human safety, and crop and weed management benefits.

For further information on current minor use permits, visit http://www.apvma.gov.au

Herbicide resistance

Herbicide resistance develops when the same herbicide Mode of Action (MOA) is used repeatedly over time on one site. Eventually, resistant weeds will be observed and control using the existing herbicide will become less effective.

Key points

Herbicide-resistant weeds are found in all the main cropping regions of Australia, and includes several species which are already considered amongst the most important weeds of vegetable production.

The problem is getting worse, with more herbicide resistant weed populations observed in a growing number of regions, and with a growing number of herbicide MOAs becoming vulnerable.

Implementing and persisting with an IWM strategy that uses a range of non-herbicide weed control tactics and avoiding reliance on a narrow range of herbicides (or MOAs) will be important ways in which growers can reduce the risk of herbicide resistance developing on their farm – or which can be used to manage herbicide-resistant weed populations.

Together, these approaches will help maximise the long-term effectiveness of the relatively limited range of herbicides available to Australia's vegetable industry.

Figure 3-7. Cases of common sowthistle (Sonchus oleraceus) *resistance to herbicides appear to be growing in Australia's broadacre grains and cotton industries, and may become an issue in vegetable production (Location: Myalup, Western Australia).*

Figure 3-8. Wild radish (Raphanus raphanistrum) *herbicide resistance in Australia is a notable issue in broadacre production in New South Wales, Victoria, South Australia and Western Australia, and has been identified in herbicides from a number of different groups.*

Figure 3-9. Wild radish (Raphanus raphanistrum) *herbicide resistance is suspected at this site in Tasmania, where parts of the fallow paddock have a relatively heavy wild radish weed burden while others are relatively clean. However, herbicide resistance testing is required to confirm this.*

What causes herbicide resistance?

Resistance generally occurs when 'selection pressure' removes plants susceptible to the herbicide from the weed population, but allows those that are resistant to the herbicide to survive and produce seed. Over time, this increases the population of herbicide-resistant plants, particularly if the survivors are not controlled using other methods.

Resistance will remain an issue for as long as there are viable seed from herbicide-resistant plants in the soil.

How extensive is herbicide resistance in Australia?

Herbicide-resistant weeds are found in all main cropping regions of Australia. Considerable work has been completed within the grains and cotton industries to identify herbicide-resistant weeds.

Resistance is most notable amongst grass species, although a number of resistant broadleaf weed species have also been identified in Australia:

- more herbicide-resistant populations of key weed species are being identified across Australia;
- additional herbicide-resistant weed species are being identified; and
- more herbicide MOAs are becoming vulnerable to resistance from certain weeds.

Table 3-1 lists relevant weeds, including herbicide group/s and states where resistance had been identified. Not all herbicides in this table were registered for use in vegetable production at the time of writing.

Table 3-1. Selection of herbicide-resistant broadleaf weeds considered based on industry survey (Kristiansen et al. 2014) to be important to Australian vegetable production. Sources and full lists: Preston (2019) and GRDC (2018).

Weed species	Herbicide group/s	Example herbicide	State/s
Blackberry nightshade (*Solanum nigrum*)	L	Paraquat, diquat	SA
Capeweed (*Arctotheca calendula*)	L	Paraquat, diquat	Vic
Common sowthistle (*Sonchus oleraceus*)	B M I	Chlorsulfuron Glyphosate 2, 4-D	Qld, SA, Vic, WA NSW SA
Dense-flowered fumitory (*Fumaria densiflora*)	D	Trifluralin	NSW, SA
Dwarf nettle (*Urtica urens*)	C	Simazine, atrazine	Vic
Flaxleaf fleabane (*Conyza bonariensis*)	M B L	Glyphosate Chlorsulfuron Paraquat	NSW, Qld, SA SA SA
Prickly lettuce (*Latuca serriola*)	B M	Chlorsulfuron; metosulam Glyphosate	SA, Vic Vic
Turnip weed (*Rapistrum rugosum*)	B	Chlorsulfuron	NSW, Qld
Wild radish (*Raphanus raphanistrum*)	B C F I M	Chlorsulfuron; metosulam; Imazapic; imazapyr Simazine; atrazine; metribuzin Diflufenican 2, 4-D Glyphosate	NSW, SA, Vic, WA WA SA, Vic, WA SA, Vic, WA WA
Wild turnip (*Brassica tournefortii*)	B	Chlorsulfuron; metosulam	SA, WA

Is herbicide resistance a problem in vegetable production?

Some instances of herbicide resistance have been anecdotally noted on Australian vegetable farms, and the issue is likely to become more significant.

Significant broadleaf weeds for vegetable growers that have shown herbicide resistance at the time of writing in Australia include dwarf nettle (*Urtica urens*), wild radish (*Raphanus raphanistrum*), blackberry nightshade (*Solanum nigrum*), and common sowthistle (*Sonchus oleraceus*) (Table 3-1).

Overseas, herbicide resistance or reduced herbicide effectiveness has been identified in several other key broadleaf weeds, including fat hen (*Chenopodium album*), marshmallow (*Malva parviflora*), pigweed (*Portulaca oleracea*), amaranth (*Amaranthus* spp.), and chickweed (*Stellaria media*).

Vegetable growers have a relatively limited range of herbicide choices available, particularly for broadleaf species, making herbicide resistance an especially important issue.

How can I minimise the risk of herbicide resistance developing on my farm?

It is important to use existing herbicides strategically to ensure they remain effective for a longer period of time. This may include:

- rotating **herbicide MOAs** (where possible using registered options in a particular crop) to reduce the risk of weeds that are resistant to a particular MOAs from becoming more prevalent;
- relying to a greater extent on **pre-emergent herbicides** (see 'Pre-plant/pre-emergent residual herbicides'; where registered in the crop), as resistance appears to be most relevant to post-emergence and non-selective herbicides;
- ensuring that herbicide use **follows label directions**, especially relating to recommended rates and weather conditions, as less than optimal use can encourage resistance; and
- using a **double knockdown** herbicide strategy to ensure that resistant individual plants do not survive.

The overall objective should be to reduce the herbicide-resistant weed seed bank over time by ensuring that herbicide-resistant weed populations do not produce seed. This is unlikely to be achievable by using a single management technique.

The mix of options used, their relevance and timing will depend on your crops, climate, annual production cycle, farm size and scale, other forms of production, and dominant weed species. These are summarised in Table 3-2.

Table 3-2. Non-herbicide weed management methods that may be used to help address herbicide-resistant weed populations at different times in the annual production cycle.

Method	Notes	Pre-plant and bed formation	Within the growing crop	Post-harvest and fallow
Stale or false seed beds	Where time permits within the growing cycle. May not suit intensive production.	X		
Tillage	To ensure that weeds do not produce seed, whether growing post-harvest, in the fallow, before crop sowing/planting, and within growing crops (inter-row tillage).	X	X	X
Inversion tillage	To bury herbicide-resistant weed seed at depth. **Please review the risks of this approach closely before considering**.			X
Farm hygiene	Use within the crop and surrounding non-crop areas where herbicide-resistant weeds may be present.	X	X	X
Hand weeding	Remove resistant weed survivors before they produce seed. **Take weeds away to burn pile or composting facility**.	X	X	X
Cover crop	To suppress weed growth using a dense cover crop canopy. May allow different selective herbicides to be used.			X
Crop rotation	Introduce different cash crops into the rotation. May allow different selective herbicides to be used.			X

Key references and further reading

Herbicide resistance research is well advanced in the Australian grains and cotton industries, and vegetable growers can certainly benefit from the findings of this important work. Examples include:

Cotton Research and Development Corporation. 2013. WEEDpak: a guide to integrated weed management in cotton. Narrabri: Cotton Research and Development Corporation.

GRDC. 2012. Herbicide resistance fact sheet: Northern region, cropping with herbicide resistance. Grains Research and Development Corporation.

Preston, A.L. (Ed). 2019. Integrated weed management in Australian cropping systems. Grains Research and Development Corporation.

A number of websites also provide updated information on herbicide resistance:

Australian Herbicide Resistance Initiative. https://ahri.uwa.edu.au/

Australian Glyphosate Sustainability Working Group. http://glyphosateresistance.org.au

International Survey of Herbicide Resistant Weeds: http://www.weedscience.org/

Part 3B: Mechanical control

Mechanical tillage or cultivation, in combination with herbicide use (see 'Part 3A: Chemical weed management'), is the most common form of pre-plant and early post-emergence weed management used on Australian vegetable farms. The crop fallow and pre-plant period is the ideal time to manage weeds so that the crop is planted into a weed-free bed, however tillage can also have a role to play once many vegetable crops are growing. Here, several options are summarised:

- fallow and pre-plant tillage, during the fallow period as well as during and after crop beds are formed.
- inter-row tillage between the crop beds or rows, used at various stages in the crop life cycle depending on the crop being grown;
- inversion tillage to invert the top layer of soil and bury weed seeds at a depth from which they are less likely to germinate; and
- stale and false seed beds, with crop beds prepared several weeks before the crop is established, and weeds controlled repeatedly using either a shallow till or non-selective herbicide application, to reduce the weed seed bank.

Depending on the crop and weed burden, these options may be used strategically in various combinations as part of your overall integrated weed management approach.

This may reduce reliance on the limited range of herbicides available within the vegetable industry, and help minimise the risk of herbicide resistance. However, growers should always be aware that excessive tillage can have negative impacts on soil structure and function.

Fallow/pre-plant tillage

Tillage following harvest, during the crop fallow period, during bed formation and before the crop is sown or transplanted, is used to kill existing weeds or to stimulate growth of weeds which are then controlled either with additional tillage operations or herbicide.

It is used extensively by most Australian vegetable growers, and it is one of the cheapest and most effective weed control options available in vegetable production systems.

Figure 3-10. Fallow tillage is carried out on this mixed lettuce and broadacre farm near Virginia, South Australia.

Figure 3-11. Bed formation provides growers with an opportunity to manage weeds through tillage before the crop is sown. Beyond this point in the crop life cycle, tillage for weed management utilises more specialised approaches that may not be relevant on all farms, such as stale or false seed beds and inter-row tillage (Location: Myalup, Western Australia).

Advantages

Out of the various weed management methods available, fallow and pre-plant tillage is a relatively cheap and easy option for growers, with the benefit of leaving no herbicide residues and of incorporating organic matter from crops and/or cover crops into the soil.

Fallow and pre-plant tillage can be used to break seed dormancy and encourage germination of new weed cohorts which may then in turn be controlled through an additional shallow till or herbicide application. Over time, this approach can help reduce the weed seed bank within your vegetable paddocks.

Disadvantages

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 and biological activity.

Tillage may stimulate germination of a new flush of weeds, either by moving viable seed closer to the surface, or breaking the dormancy of seed by scarifying (scratching) the seed coating. Follow-up shallow tillage or herbicides can be used to control this flush of germination, but sufficient time should be allowed before the crop is planted.

Timing

Timing is critical to ensure that fallow and/or pre-plant tillage is most effective. Delaying until the weeds are too big (particularly in the case of shallow tillage after crop beds are formed) means that some plants will not be killed by cultivation. Too early and further weeds may still emerge before or in the early stages of the cropping season. Maximum success will also be achieved if weeds are tilled before they produce seed, as this will help reduce the weed seed bank over time.

How to use

Most growers use tillage extensively in their vegetable production system. Often, tillage is used immediately after harvest to incorporate the crop residues back into the soil. This approach also applies when incorporating a cover crop to improve soil structure and health (see Part 3E 'Green manure and biofumigant cover crops')

Tillage before crop sowing or planting (and as a part of bed formation) is used almost universally in the Australian vegetable industry. Minimum tillage is still relatively unusual in Australian vegetable production, though some growers are having success using minimal tillage approaches such as living and killed mulches (see 'Cover crop mulches'), and strip till (see 'Strip tillage').

Where fallow periods are included in the annual crop cycle, tillage and non-selective herbicides appear to be the main two methods used to manage weeds. However in some regions production is carried out year-round with only a few days break between crops, and fallow tillage is not applicable.

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 immediately before planting (see also 'Stale and false seed beds').

Several of types of tillage implements are available including rotary hoes; power harrows; disc, chisel and mouldboard ploughs; deep rippers; and various tined implements. Tined implements are preferable as they are less likely to create soil health issues.

Figure 3-12. This spading tiller is used near Richmond, New South Wales, to incorporate a trial cover crop after slashing.

Other considerations

Climatic conditions and soil moisture need to be taken into account in the decision to till. Weed control will be most successful when conditions are hot, dry and sunny. However, tilling when it is dry and windy may result in soil erosion. Tilling the soil when it is too wet or too dry can result in soil compaction and is less effective at killing weeds.

Integration with other techniques

Non-selective herbicides use may *immediately precede* post-harvest tillage, to control all weeds present in the recently harvested crop. Spraying off the crop before incorporation may also make incorporation tillage easier and more effective.

Non-selective herbicides may also be used *alongside* post-harvest, fallow and pre-plant tillage to help maintain a clean paddock in the period before the next crop is planted or sown.

Techniques to *immediately follow* post-harvest, fallow and pre-plant tillage may include **stale or false seed beds** to reduce the weed seed bank within the formed beds, **pre-emergent herbicide** if registered for your crop, **inter-row tillage**, selective **hand weeding** within the crop beds to remove remaining weeds, or potentially selective **thermal weeding** (steam or flame weeding).

Integration with other techniques will depend on farm circumstances (crops, soil and climate, staff, budget, and timing within crop cycle).

Maximising success

- Time the tillage operation to manage relatively small weeds that have not yet produced seed.
- Till in warmer, dry and still conditions to maximise weed eradication.
- Avoid tilling in moist conditions to limit soil compaction and increase weed kill.
- Use tined tillage implements and conduct shallow tillage where possible to minimise impacts on soil structure and health.

Key references and further reading

Bowman, G. 2002. Steel in the field: A farmer's guide to weed management tools. Beltsville: Sustainable Agriculture Network.

Eldridge, S. 2004. Soil management for commercial vegetables & small crops. Richmond: NSW Agriculture.

Henderson, C.W. and A.C. Bishop. 2000. Vegetable Weed Management Systems, pp. 355-372 in Sindel, B.M. (Ed) Australian weed management systems. Meredith: R.G. and F.J. Richardson.

Inter-row tillage

The 'inter-row' (the space between crop rows on top of the raised crop bed, or between the beds themselves) can be a source of weed seeds in vegetable paddocks, while inter-row weeds can also have an impact on crop yield and quality.

In some crops (e.g. lettuce), inter-row spacing may only be relatively narrow, while in other crops (e.g. cucurbits) it may be wider. Effective weed management in this space is likely to help reduce the weed burden across the paddock over time.

Inter-row tillage involves tilling or cultivating the top of the crop beds and/or between the raised crop beds. For many vegetable crops, shallow tillage within the crop beds after crop emergence or transplanting may provide the best opportunity to greatly reduce the early in-crop weed burden, before the crop plants have had the chance to shade the beds fully.

It offers a cost-effective alternative to inter-row herbicide application (for example, using a shielded sprayer; see 'Herbicide control in specific locations') or possibly to hand weeding (see 'Hand weeding'). It can also be used to complement those practices. It is relatively common in organic vegetable production, and is also used by some conventional growers.

If inter-row weeds are allowed to produce seed during crop cycles, it will be more difficult to reduce the weed burden across the paddock over the longer-term. This can also reduce the benefit of your other weed control tactics.

Figure 3-13. A scuffler used for inter-row tillage on a vegetable farm near Gatton, Queensland. The tine spacing and height have been set up to manage weeds both within the wheel tracks of a lettuce crop, and between the lines of vegetables on top of the raised crop bed.

Figure 3-14. Customised inter-row cultivator used for inter-row tillage in a leek crop near Clyde, Victoria. Note that the implement cultivates both the wheel tracks and the sides and centre of the raised crop bed.

Figure 3-15. Weedfix cultivator used for inter-row tillage near Clyde, Victoria. This photo illustrates one of the benefits of inter-row tillage. By 'hilling' a little soil into the plant rows, the tillage pass may be covering and suppressing growth of some recently germinated weeds.

Advantages

- Particularly relevant to transplanted vegetable crops within a few days of planting. The crop will establish relatively quickly, be less likely to be damaged by inter-row tillage, and more likely to form a canopy before subsequent weed cohorts germinate.
- Reduces the weed burden in the current crop, with potential benefits in enhanced crop quality and reduced contamination and time required during processing.
- Reduces the number of weeds that produce seed, contributing to gradual reduction in the weed seed bank.
- May provide some benefits within the crop rows, if the implement 'hills' the soil within the crop row, and suppresses recently germinated weeds.
- Can generally be implemented without causing damage to plants or plant roots, providing the tillage operation is relatively shallow and completed relatively early in the life of the crop.
- Using inter-row tillage may mean not having to rely on inter-row herbicide application, which may cause damage to crop plants through spray drift, even when all efforts have been made to avoid drift.
- Similarly, it may be easier to carry out inter-row tillage than to weed the inter-row space by hand.

Disadvantages

- Considerable care and accuracy is required to avoid damage to crop leaves and roots. GPS systems can help improve accuracy of operations from sowing/planting to tillage for weed control.
- Where used within the raised crop bed, inter-row tillage is likely to be less beneficial in sown vegetable crops. More recently germinated crop plants, or crops that are slower growing, are more likely to be injured by inter-row tillage, and high levels of weed control success are more likely to be associated with a greater amount of crop damage.
- Where inter-row tillage is being used in a plastic mulch crop (between the plastic mulch-covered beds), particular care will be needed to ensure that the tillage operation does not tear and/or lift the plastic mulch that has been covered with soil long the edges of the crop beds.
- Inter-row tillage may only keep inter-row weeds under control for a relatively limited time in the crop life-cycle (particularly in slower-growing cash crops), and may be less effective in removing larger weeds (Figure 3-16).
- Inter-row tillage may contribute to soil compaction and reduced soil quality if used too regularly.
- Not suited to use within raised crop beds for crops that are grown across the entire bed (e.g. some leafy crops).
- Excessive 'hilling' of soil within the crop rows may reduce crop quality by creating dirty produce.

Figure 3-16. Inter-row tillage used within a leafy vegetable crop near Gingin, Western Australia (left), and in a leek crop near Clyde, Victoria (right). These photos illustrate one of the limitations of inter-row tillage. Because the tillage equipment is only able to follow the inter-row spaces, weeds within the plant rows (the 'intra-row') are able to survive the tillage operation. Larger weeds are also capable of surviving within the inter-row, as the second photo illustrates. Some of these weeds may later reduce crop yield or contaminate the crop at harvest. Follow up activities such as hand weeding may be required to control remaining weeds, particularly larger ones or those that are about to produce seed.

Timing

Inter-row tillage operations need to be timed carefully within the crop life cycle. Waiting until the cash crop has grown relatively large may result in damage to crop plant roots (or even above-ground parts) that have spread into the inter-row space. This will result in reduced yield and/or quality of the final crop, and potentially outweigh any benefits resulting from reduced weed presence.

On the other hand, choosing to undertake inter-row tillage when the crop plants are relatively small may give the next cohort of weeds time to germinate and establish in the inter-row space later in the crop cycle. Ultimately, it may then be too late to manage these weeds without damaging the crop plant roots.

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, potentially exposing crop plant roots to damage.

How to use

Considerable accuracy is required when using inter-row tillage equipment, since slight errors can result in damage to crop plants. Establishing exact and consistent distances between crop lines within the beds will help make inter-row tillage possible.

GPS technology (see 'Automation and guidance technology') will help ensure the tractor completing the inter-row tillage operation maintains the correct, making inter-row tillage quicker and reducing the risk of damage to crop plants. However, an experienced operator may be able complete inter-row tillage operations relatively quickly without need for GPS guidance.

Suitable tillage equipment options will depend on the width of the inter-row space. In some production systems (such as cucurbits planted in plastic mulch) the inter-row space is likely to be relatively wide, and may potentially be tilled with standard equipment already in your shed. In others (e.g. loose leaf, carrots, brassicas) it is likely to be relatively narrow. In this case, specialised or customisable tillage equipment will be required to till on top of the raised crop beds and/or within the wheel tracks.

Examples include customised scufflers (Figures 3-13 and 3-14), specialised equipment such as the 'Weedfix' cultivator (Figure 3-15), basket weeders and flexible tines. These may be customised with a range of disc, plate and hood fittings to protect the crop and suit a particular inter-row width. Other options include spring-tine, drag or chain harrows, arrow-head cultivators, torsion weeders, finger weeders, and vertical brush weeders.

Tilling depth: inter-row tillage should only be completed to a depth sufficient to control young weeds. Deeper cultivation can break or damage crop plant roots, having a negative impact on crop nutrient and water uptake, and reduce final yield. The ideal depth can depend on crop variety. As an example, a maximum depth of approximately 8 cm has been suggested for inter-row tillage in cucurbit crops, and approximately 3 cm for shallow-rooted crops such as lettuce.

Intelligent intra-row tillage equipment (to be used within the rows of vegetables on a raised vegetable bed) is now being developed, using sensor technology to differentiate crop plants from weeds and soil, and to guide tillage implements around crop plants. This is discussed further in the section 'Robotic weeding' (see also Figure 3-17). In time, this technology may make both inter- and intra-row tillage operations possible.

Figure 3-17. An example of the robotic weeding technology under development at the time of writing (Location: Richmond, New South Wales).

Other considerations

Transplanted crops are also more likely to gain a competitive advantage over weeds post-till given their height advantage and root development relative to sown crops. This means that inter-row tillage may be better suited to transplanted vegetable crops. Crop plants should have a size advantage over weeds to make inter-row tillage more effective.

Although inter-row weeds are often considered to have little negative impact on the final yield of the current crop, it is important to keep in mind that weeds producing seed in the inter-row space are contributing to the weed seed bank both within and between crop rows, in future crops.

Integration with other techniques

Techniques to *immediately precede* inter-row tillage will include methods to produce a clean, weed-free crop bed for planting or sowing. They may include **fallow and pre-plant tillage**, **fallow and pre-emergent/pre-plant herbicide** (if registered for the crop), **stale or false seed beds** to reduce the weed seed bank within the formed beds, and potentially broad-scale **thermal weeding** (steam or flame weeding).

Techniques to *immediately follow* inter-row tillage may include **hand weeding**, **shielded herbicide application**, or potentially selective **thermal weeding** (steam or flame weeding), to control surviving inter-row weeds.

Integration with other techniques will depend on farm circumstances (crops, soil and climate, staff, budget, and timing within crop cycle).

Maximising success

Some Australian growers consider inter-row tillage to be a critical part of their overall weed control strategy, particularly when its implementation is timed appropriately within the crop life cycle. This means:

- using inter-row tillage when weeds have fairly recently germinated and can be controlled effectively using a shallow tillage pass;
- completing the tillage at a time in the crop life cycle where the crop plant roots will not be damaged; and;
- timing the activity so that the crop will shade the inter-row space (if relevant) before the next flush of weeds become too large.

It is likely to be beneficial to follow up in the crop beds with **hand weeding**, to minimise the number of weeds producing seed, and to minimise crop contamination at time of harvest.

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Inversion tillage to manage the weed seed bank

Inversion tillage is only likely to be considered where the weed burden is particularly severe, which means that there is a large and difficult to manage weed seed bank in the first few centimetres of soil. A deep, one-off inversion till may bury this weed seed bank below the depth from which weeds usually germinate. However, the approach is not without risks and potentially damaging side-effects.

Advantages

Inversion tillage may be considered as an option to reduce a severe weed seed burden at the soil surface by burying the seed at a depth from which they are unlikely to germinate.

Disadvantages

- Many weed species possess seed with great longevity, and are capable of remaining dormant for many years within the soil. Burying this weed seed bank at a greater depth can mean that another inversion operation, even decades in the future, may result in a large flush of dormant weed seed germinating unexpectedly.
- Similarly, the original inversion operation may expose a large buried seed bank which had remained dormant since a historic deep till or inversion till had been completed, and result in new weed problems within your crop.
- Although an inversion tillage operation may bury surface seed at a depth from which it cannot germinate, it also limits their exposure to predation (for example by insects) and to drying out and losing their viability more quickly.
- Inversion usually means that the buried seed bank cannot be reduced over time by using weed management approaches such as pre-emergent herbicides (see 'Pre-plant/pre-emergent residual herbicides'), hand weeding (see 'Hand weeding'), or even stale and false seed beds (see 'Stale and false seed beds'), as seed are buried below the reach of conventional management options.
- Inversion tillage may bury your best quality soil, which has been improved over time with fertiliser application, and bring to the surface a poorer quality soil layer which requires work to improve. This may result in lower yielding crops in the short- to medium-term.
- Soil inversion can also increase the risk of erosion or surface layer loss by disturbing the soil structure.

Timing

Inversion tillage will only be feasible during the crop fallow period. It may also require an extended crop fallow, if work is required to improve the health of the soil following the inversion operation.

How to use

Inversion tillage involves using traditional tillage implements such as mouldboard ploughs or disc ploughs to invert the top layer of soil (typically between 15 and 30 cm) to bury any near-surface residues – including weed seeds – at a greater depth.

Other considerations

Table 3-3 lists some of the most important weed species of Australian vegetable production. Although an inversion till operation will bury these seed below the depth from which they germinate, it is important to note that a proportion of the weed seed will remain viable for up to several decades.

Table 3-3. Optimal weed seed burial depth in the soil and seed longevity for several common weed species of Australian vegetable production.

Weed species	Optimal burial depth (mm)	Seed Longevity
Amaranth (*Amaranthus* spp.)	10 mm to 15 mm	Up to 40 years
Blackberry nightshade (*Solanum nigrum*)	2.5 mm to 15 mm	Up to 40 years
Chickweed (*Stellaria media*)	5 mm to 10 mm	Up to 60 years
Common groundsel (*Senecio vulgaris*)	0 mm	Up to 6 years
Common sowthistle (*Sonchus oleraceus*)	0 mm to 10 mm	Up to 8 years
Dwarf nettle (*Urtica urens*)	0 mm to 25 mm	Up to several decades
Fat hen (*Chenopodium album*)	2 mm to 50 mm	Up to several decades
Marshmallow (*Malva parviflora*)	5 mm to 20 mm	Up to several decades
Pigweed (*Portulaca oleracea*)	0 mm	Up to 40 years
Potato weed (*Galinsoga parviflora*)	0 mm to 10 mm	Up to 10 years
Wild radish (*Raphanus raphanistrum*)	10 mm	Up to 20 years
Wireweed (*Polygonum aviculare*)	0 mm to 30 mm	Up to 60 years

Integration with other techniques

Inversion tillage can be considered a standalone and usually infrequent attempt to reduce the weed burden by burying the problematic weed seed bank.

This means that it does not need to be considered a common part of an ongoing integrated weed management strategy. However, it is likely to be used following harvest or in the fallow period, and most likely within a clean crop bed that has been recently controlled for weeds.

The decision to use inversion tillage in a vegetable production system should be taken with great care, closely considering the range of potential consequences, positive and negative.

Stale and false seed beds

Stale seed beds involve preparing a seed bed up to several weeks before crop planting, and then leaving the bed undisturbed. In this period, weeds are allowed to germinate and grow, possibly stimulated through irrigation, and then controlled with a knock-down herbicide just before the crop is planted. Flaming may also be used in place of knock-down herbicide to manage recently germinated weeds.

False seed beds are similar, but involve repeated shallow cultivations or knock-down herbicide applications to prepared crop beds over several weeks before planting or sowing. Growers often use a mix of shallow cultivation and knock-down herbicides or flaming if they are using a false seed bed, although the mix of viable control approaches will depend on available equipment as well as time.

The goal of using stale or false seed beds is to stimulate germination of weeds near the soil surface, while controlling these recently germinated plants well before they have had a chance to produce seed. This can have an important impact on reducing the weed seed bank.

Figure 3-18. Planting leeks into a stale seed bed near Clyde, Victoria.

Advantages

- Repeated shallow tillage in a false seed bed reduces the number of weed seeds in the soil as well as weed diversity.
- Reducing the number of weeds germinating during early growth stages of the vegetable crop will give the crop a head-start (particularly seeded crops).
- Over time, stale and false seed beds can reduce reliance on pre-emergent and post-emergent herbicides.
- Research suggests that repeated shallow tillage in a false seed bed may be of greater benefit than flaming in managing recently germinated weeds, and is therefore especially relevant to organic vegetable production. Integrating a false seed bed with multiple flaming passes achieves the greatest success.

Disadvantages

- Lack of time is a major limiting factor. In intensive production systems with little break between crops, it can be difficult to fit a stale or false seed bed into the annual cycle (Figure 3-19).
- Some soil types may not be suited to stale or false seed beds, particularly those that rapidly form a crust that can make sowing or transplanting less effective. In these cases, the crop beds may need to be formed immediately before sowing/transplanting.
- Delaying crop planting to allow a stale or false seed bed to be implemented may be detrimental to crop yield if it means the ideal crop planting window is missed.

Figure 3-19. For growers in peri-urban regions, such as the Werribee district in Victoria, relatively small property sizes and intensive year-round production means that three to four week long stale or false seed beds may not fit into the annual production cycle, though a shorter-term seed bed (for example, one week) may still have some benefits, especially if irrigation can be used to strategically stimulate weed germination.

Timing

Stale and false seed beds are always implemented in freshly-formed crop beds before a crop is sown or transplanted. Sufficient time will be required within the annual crop cycle to employ this approach – approximately 20 to 30 days is considered ideal, although longer or shorter durations may provide some benefit for reducing the weed load.

How to use

Beds are formed as normal, but up to several weeks before the crop is sown or transplanted.

Soil disturbance is then limited to shallow tillage at most, in the period following bed formation and before crop establishment. This means that seeds buried below the top layer of soil are not brought closer to the surface for germination.

Broad-spectrum or non-selective herbicides (see 'Fallow and postharvest herbicides') are generally used in stale and false seed beds. Options may include glyphosate, paraquat, diquat, pendimethalin and oxyfluorfen. Using herbicides only will allow zero tillage within the beds before the crop is established.

Alternatively, repeated shallow tillage to a depth of approximately 1cm may be used to control recently germinated weeds. It also has the advantage of stimulating the next flush of weed germination, for further control with a second or subsequent shallow tillage pass.

Organic vegetable growers may use thermal weed control (see 'Thermal (flame and steam) weeding') to manage recently germinated weeds in a stale seed bed.

Other considerations

Australian vegetable growers have adapted stale and false seed bed approaches to suit their needs in various ways:

- Implementing an approximately one-week stale seed bed in an intensive vegetable production system, with a pre-emergent herbicide applied to the bed just before crop planting.
- Implementing a one-month stale seed bed, with a non-selective herbicide applied approximately two and four weeks after bed forming.
- Fumigating the beds approximately a week before planting to reduce the weed seed bank (see 'Chemical fumigation').
- In plastic mulch systems, laying the mulch film approximately four weeks before planting, and using drip irrigation to stimulate weed germination beneath the plastic. The length of time causes many weeds to germinate and then die due to soil solarisation (see 'Soil solarisation') before the crop is transplanted. This reduces the number of weeds growing through the crop plant holes in the mulch.

Integration with other techniques

Stale and false seed beds are themselves an integrated weed management technique which may incorporate bed formation, shallow tillage, non-selective herbicides and thermal weeding depending on circumstances. Effective **farm hygiene** practices can be used to minimise the addition of new weed seed to the crop beds.

Techniques to *immediately precede* stale and false seed beds will focus on effective management of weeds within the previous cash crop, such as **post-emergence and post-plant herbicides**, **inter-row tillage**, and **hand weeding** with a focus on minimising weed seed production in the crop. They may also include fallow and postharvest herbicides (if registered for the crop).

These same techniques will also *immediately follow* stale and false seed beds within the subsequent cash crop, with the goal of controlling surviving weeds before they produce seed.

Integration with other techniques will depend on farm circumstances (crops, soil and climate, staff, budget, and timing within crop cycle).

Maximising success

The optimal length of time for implementing a stale or false seed bed in vegetable production is approximately 20 to 30 days. One or two weed control activities (knock-down herbicide application or shallow cultivation) may be applied during this period.

This approach has been shown to provide greater crop yield and higher rates of weed control in vegetable production (Lonsbary et al., 2003).

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Part 3C: Physical control - hand weeding

Australian vegetable growers consider hand weeding to be one of the most effective ways to manage weeds – but also amongst the most expensive!

The goal of hand weeding is to follow up on control of surviving weeds missed during earlier weed control activities, and most importantly to remove weeds from the crop before they produce seed. The relevance of hand weeding on each farm will depend on available resources and the types of crops grown.

In many vegetable crops, hand weeding (including chipping with a hoe or other similar implement) is the only feasible way to manage weeds within the crop rows at later stages of the crop cycle, since there are relatively few post-plant or post-emergence selective herbicide options available in many vegetable crops.

Over time, integrating hand weeding with other approaches to manage weeds before they produce seed will improve the profitability of your farm by reducing the cost of weed control, and improving crop quality.

Hand weeding

Hand weeding involves removal of weeds directly, either by pulling weeds out of the ground by hand, or by chipping or digging them out using hand-held tools and implements. Hand weeding is an accurate and reliable method of physical weed control. It is possible to achieve a high level of selectivity and accuracy in removing weeds, especially where the individual performing the hand weeding task is suitably trained in plant identification.

Advantages

- An effective follow-up to control survivors missed by other weed control activities.
- Hand weeding can be carried out in all stages of the crop life cycle, and during any crop activity.
- Combined with other methods, hand weeding can gradually reduce the weed seed bank, eventually saving time and money.
- Can be used effectively to manage outbreaks of new weed species, or small patches of weeds, before they become a more significant problem.
- Removing weeds immediately before harvest will be important in minimising crop contamination, processing time, and may result in higher prices at market.
- Diligent application can be used to manage weeds before they produce seed, i**ncluding herbicide-resistant weeds**.
- Seeing the long-term benefits of hand weeding as a key component of IWM (few weeds within a clean crop) will improve staff morale and satisfaction.

Disadvantages

- **High cost** makes extensive hand weeding unaffordable, and perhaps most relevant in high-value crops.
- Effectiveness depends on the skill of staff to correctly identify weeds and remove without causing excessive crop damage, and their motivation to continue with this activity.
- Takes considerably longer to cover the same area as other methods such as tillage or herbicide use.
- May require additional casual staff to be put on at different times of the season, if used for extensive outbreaks.
- Physically demanding for staff, and potentially demoralising if it is being used to address large weed outbreaks.
- Given the above points, **not feasible as a broad-spectrum or wide-scale weed control technique**.

Figure 3-20. Extensive hand weeding is costly, and is more likely to be economically viable within high-value vegetable crops (Location: Katherine, Northern Territory).

Timing

Cost-effective hand weeding may mean targeting surviving weeds for control approximately 7-10 days before the crop canopy closes. This ensures that weeds germinating after canopy closure are less likely to reach maturity and produce seed.

However, hand weeding is generally applicable at any stage in the crop life cycle:

- Chipping out small weeds within the crop beds soon after the crop has been planted (Figure 3-21), to reduce the weed burden before the crop canopy closes. Ensure that damage to the crop (including plant roots) is minimised.
- Once the crop canopy has closed, remaining mature weeds may be pulled out by hand (Figure 3-22) or hoed out. If these weeds have begun to flower or set seed, take them away from the paddock and dispose in such a way that they do not increase the weed seed bank.
- Be attentive of weeds at all times when working in the paddock, and incorporating hand weeding into all activities within the crop, from sowing through to harvest but also during the fallow period.

Figure 3-21. Timing your hand weeding appropriately may involve chipping out recently germinated weeds soon before the crop canopy closes and before chipping will damage crop plants. In this way, the number of weeds present in the maturing crop are minimised (Location: Gatton, Queensland).

Figure 3-22. Pulling weeds out by hand without using an implement may be necessary to follow up on survivors in crops that form dense swards, but may also be relatively easy in lighter, sandy soils (Location: Gingin, Western Australia).

How to use

Depending on crop and soil type, hand weeding activity may involve simply pulling weeds out of the ground by hand, or it may require digging or hoeing out weeds.

Most hand weeding implements are more effective when used to manage recently germinated weeds. This means that their usefulness may coincide with the period between crop establishment and crop canopy closure (the most beneficial time to manage weeds by hand as a follow-up to other activities).

Types of hand weeding implements

A variety of long-handled hand weeding implements are available. The most commonly used type on vegetable farms is the long-handled hoe (Figure 3-23). These are often customised to local needs by vegetable growers, and may be used to remove recently germinated weeds as well as mature weeds with more developed root systems. Hoes tend to be the most versatile and efficient hand weeding implement on vegetable farms.

Long-handled oscillating stirrup hoes (Figure 3-24) are designed for removal of smaller weeds by lightly scarifying the soil surface, and feature two-sided cutting edges. Similar implements include Dutch hoes, collinear hoes, weed slicers, and wire weeders. These implements are most likely to be useful in lighter soils.

Wheeled or rotary cultivators (Figure 3-25) allow for physical cultivation within vegetable crop beds in between the line of plants. They are most suited to managing smaller weeds in lighter soils, and may provide an alternative to inter-row tillage, especially in smaller market gardens.

Some short-handled implements are also available, such as hoes, sickles and knives. However, these are rarely used on vegetable farms and are most likely to be suited to removing weeds in difficult to reach places such as close to the base of crop plants.

Figure 3-23. Long-handled hoes are the mainstay of hand weeding on vegetable farms, and may be used to remove recently germinated and more mature weeds. Many vegetable growers customise this implement to suit their particular needs.

Figure 3-24. The oscillating stirrup hoe is most effective when used to control younger, recently germinated weeds. It can be used close to crop plants, though care must be used to avoid crop damage. The blade is sharpened on both sides, allowing weeding to be completed by the operator by pulling the implement towards themselves as well as pushing it away. It is most efficient when used to slice weed roots just below the soil surface. (Location: Peats Ridge, New South Wales).

Figure 3-25. Rotary cultivators are suited to larger hand weeding tasks involving young weed plants. As shown here, they can be used effectively within the crop bed between the planting lines, even when the crop is relatively mature. They appear to be more efficient when used in light sandy soils than in heavier clay soils (Location: Richmond, New South Wales).

Other considerations

- The financial burden of hand weeding is likely to be greatest where less effective implementation of other weed control activities has allowed the weed population to expand significantly. Consider ways to improve the effectiveness of these non-hand weeding approaches first, and then use hand weeding selectively to 'mop up' survivors.
- More extensive hand weeding is most likely to be relevant to smaller vegetable farms, however the principle of removing weeds before they produce seed is relevant to all farms, and is a cornerstone of effective IWM.
- Transplanted crops are also likely to require less hand weeding than sown crops, as the crop plants are able to out-compete germinating weeds sooner after the beds have been established for the crop. Some vegetable crops may also be more competitive than others, and require less hand weeding.
- Combine in-crop hand weeding with effective management of weeds in wheel tracks and irrigation lines, potentially including options such as precision tillage or herbicide application, or hand weeding of occasional plants found in these adjacent non-crop areas.

Integration with other techniques

Hand weeding can be used strategically with any other weed control methods employed, at most stages of the crop life cycle, and within all vegetable crops, generally as a supplementary option.

Integration with other techniques will depend on farm circumstances (crops, soil and climate, staff, budget, and timing within crop cycle).

Maximising success

A few basic principles will underpin successful use of hand weeding in vegetable production:

- Always aim to remove weeds before they have produced seed.
- Dispose of all weeds outside the crop after removing by hand (for example a burn pile or a composter), rather than throwing weeds onto the ground within or near the crop. Take a bucket or sack into the crop to carry weeds removed by hand away from the crop site.
- **Be diligent**. Always be on the lookout for survivor weeds, and remove them by hand as soon as they are seen.
- **Be persistent**. It may take several seasons for hand weeding (combined effectively with other weed control methods) to deliver notable reductions in the weed seed bank. But when this occurs all weed control methods (including hand weeding) will be less time-consuming and expensive.
- **Do not just rely on hand weeding**. Integrate strategically with other approaches for maximum benefit.

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Part 3D: Synthetic and natural mulches

In this section, the following mulch options are discussed:

- Plastic mulch films, which are a cornerstone of weed management as well as providing other significant benefits in certain high-value vegetable crops.
- Biodegradable mulch films, an emerging product proposed as a sustainable alternative to plastic mulch film.
- Living and killed cover crop mulches, planted before the cash crop and intended to help suppress weeds until the cash crop has matured.

Plastic mulch films

Polyethylene plastic mulch films have been available for vegetable production since the 1950s. Although they are expensive to purchase, lay and remove, they are feasible within a number of higher value vegetable crops including capsicums, tomatoes, melons, and other cucurbits.

In addition to weed control, they also deliver a range of other benefits to the crop, including soil moisture retention and greater water use efficiency, warming the soil, 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.

In Australia, black film is generally used in the cooler months or regions (Figure 3-26), and white film is generally used in the warmer months or regions (Figure 3-27), to regulate soil temperature. Clear films are also available, but are rarely used in vegetable production. Biodegradable mulch films are also under development, and are discussed in the next section.

Figure 3-26. Black plastic mulch used in a summer zucchini crop (Location: Moriarty, Tasmania).

Figure 3-27. White plastic mulch used in a winter pumpkin crop near Darwin, Northern Territory.

Advantages

- Very effective at suppressing weeds by restricting the amount of light available for seed germination.
- Considered by Australian vegetable growers to be one of the most effective forms of weed control for certain production systems.
- Negates the need for pre- or post-emergent selective herbicides, and minimises the need for in-crop weed management such as hand weeding or spot spraying.

Disadvantages

- Nutgrass (*Cyperus rotundus*) plants are capable of piercing the plastic mulch layer (Figure 3-28).
- Other weeds are also capable of growing through holes in the mulch.
- Some limited in-crop weed management therefore likely to be required.
- Considerable additional expense in purchase, laying, removal and disposal.
- Waste management concerns may mean disposal is restricted in some situations.

*Figure 3-28. Nutgrass (*Cyperus rotundus*) is capable of piercing plastic mulch films. This causes problems after crop harvest for removal of the plastic mulch from the crop beds, and also allows nutgrass to persist within plastic mulch production systems (Location: Bundaberg, Queensland).*

Timing

Laid on the crop beds before the crop is transplanted, and removed postharvest.

How to use

Plastic mulch films are laid on just-formed crop beds immediately before planting, using a roller unit attached to the back of the tractor. An irrigation tape is laid beneath the film to allow the crop to be watered and fertilised by trickle irrigation and fertigation. The mulch is pierced at regular spacings and transplanted crop plants planted into the holes.

Care should be taken during application and during the life of the crop to avoid piercing the mulch film accidentally, as this can open up spaces for weeds to germinate and grow.

Some growers may lay the plastic mulch film several weeks before planting in a variation on a stale seed bed (see 'Stale and false seed beds'), irrigating the soil and encouraging weed seed to germinate beneath the plastic film layer, where the young weeds will die due to soil solarisation (see 'Soil solarisation').

After harvest, conventional plastic mulches and irrigation tape are removed from the crop beds, generally by being rolled onto a unit attached to the tractor.

In both cases, the paddock is then managed through fallow, and subsequent non-mulched crops if applicable, before the process begins again.

Some growers have experimented with leaving plastic mulch on the crop beds and planting a second crop with the same mulch layer. This has had mixed success regarding moisture and heat retention, and weed control.

Where weeds grow through the crop plant holes or other holes made in the mulch film during laying or crop management (Figure 3-29), other weed control methods may be needed in the crop beds, notably hand weeding or spot-spraying using a non-selective herbicide.

Weed control will still be necessary between the crop rows, either through tillage that avoids damaging the plastic mulch, or using a shielded spray unit to apply non-selective herbicide. The best time to carry out this activity will be early in the crop life before crop plant root systems have started to utilise the inter-row space.

*Figure 3-29. In this cucurbit crop near Darwin, Northern Territory, giant pigweed (*Trianthema portulacastrum*) has successfully germinated and grown through a hole made in the mulch while the mulch film has been laid. Weeds can similarly grow and thrive within the holes made in the plastic mulch film for the transplanted crop plants, potentially out-competing the crop plant and making control difficult*

Other considerations

In some regions, local government landfill sites are no longer accepting plastic mulch waste. Where it is still accepted, depositing the waste mulch in landfill is becoming more expensive. Burning the used mulch once it has been removed has significant environmental impacts and is not recommended.

Growing concerns over the environmental impact of conventional plastic mulch could mean that conventional plastic mulch is phased out in the future. Biodegradable film alternatives (see 'Biodegradable mulch films') may become more common providing they are as effective as conventional plastics, while other possibilities include living or killed mulches (see 'Cover crop mulches'), or strip tillage (see 'Strip tillage').

Research suggests that clear or translucent mulch films may be more effective than black plastic in reducing nutgrass tuber production, potentially due to higher temperatures under these films.

Integration with other techniques

Plastic mulch films may allow some weeds to grow in the crop beds due to piercing of the mulch (deliberately for crop plants, or accidentally during laying or crop management). Limited weed management may be required within the crop beds (**hand weeding**, spot-spraying with **non-selective herbicide**). Inter-row weed management will still be needed, including **shielded herbicide application** or **inter-row tillage**.

Techniques to *immediately precede* plastic mulch will focus on effective management of weeds in the fallow. This is likely to include **fallow and postharvest herbicides** (if registered for the crop), and **tillage** as well as **stale or false seed beds**.

These same techniques will also *immediately follow* plastic mulch removal after harvest. However, a **non-selective herbicide** may be applied to postharvest crop plants and weeds before the mulch is removed, to make removal easier.

Integration with other techniques will depend on farm circumstances (crops, soil and climate, staff, budget, and timing within crop cycle).

Maximising success

- A fumigant (see 'Chemical fumigation') may be applied to the soil before the mulch is applied to increase the effectiveness of black plastic as a pest and disease control agent. Fumigation can also be an effective method of controlling weeds.
- Weeds may also grow through the planting holes in the plastic mulch where the crop is planted, or where the plastic has been pierced during laying. Care should therefore be taken to minimise holes in the film layer.
- Effective inter-row weed management will help reduce the weed seed bank.

Biodegradable mulch films

Biodegradable mulch films are proposed as a sustainable alternative to plastic mulch.

They are made up either of biodegradable polyethylene or biodegradable starch and polyesters, and are designed to degrade several months after being laid. Ideally, they will deliver the same benefits as plastic mulches but at the same time degrade sufficiently that they may be cultivated into the field post-harvest, leaving no toxic residues or plastics in the soil.

At the time of writing their use in the Australian vegetable industry appears to be largely restricted to experimental use, including some on-farm trials.

Other alternatives such as paper-based mulches are also available, but a key limitation with these products is their tendency to begin breaking down earlier in the crop life cycle.

Advantages

- Crop yield can be comparable to conventional plastic mulch films.
- Becoming more cost-effective; closer to the combined purchase, removal and disposal costs of conventional plastic.
- Sustainable alternative to plastic mulch films if these become less socially and environmentally acceptable.
- Does not need to be removed from the paddock postharvest – incorporate through tillage, and subsequently broken down further by soil microbial activity.

Disadvantages

- At the time of writing, biodegradable mulches were considerably more expensive than conventional plastic film to purchase.
- Application requires additional care and time to avoid piercing.
- Nutgrass (*Cyperus rotundus*) plants are capable of piercing the biodegradable mulch layer.
- Loss of bed coverage due to damage to the biodegradable mulch during laying or during farm operations, or a shorter life span, can result in more weeds within the crop beds than when conventional plastic mulch is used (Figure 3-30).
- Uncertainty over the impacts of biodegradable plastic mulches on soil health and crop productivity, compared to conventional plastic film.
- Not suitable for use alongside chemical fumigation.
- Still under development, though results appear to be promising.

Timing

Laid on the crop beds before the crop is transplanted, with remains tilled into the soil postharvest.

How to use

As with plastic mulch film, biodegradable mulches are laid on just-formed crop beds immediately before planting, using a roller unit attached to the back of the tractor. An irrigation tape is laid beneath the film to allow the crop to be watered by trickle irrigation and fertigation. The mulch is pierced at regular spacings and transplanted crop plants planted into the holes.

Additional care should be taken during application and during the life of the crop to avoid piercing the mulch film accidentally, as this can open up spaces for weeds to germinate and grow.

After harvest, the irrigation tape will still need to be removed from the crop beds, however the mulch film should be ready to be incorporated using postharvest tillage.

Figure 3-30. Biodegradable mulch film during the breakdown phase near Childers, Queensland (Source: M Everett, Research Agronomist, Valencia Ecosystems).

Where weeds grow through the crop plant holes or other holes made in the mulch film during laying or crop management, other weed control methods may be needed in the crop beds, notably hand weeding or spot-spraying using a non-selective herbicide. At the time of writing, this issue is likely to be more significant than in the case of comparable plastic mulch film.

Weed control between the crop rows is still necessary, either through tillage that avoids damaging the plastic mulch, or using a shielded spray unit to apply non-selective herbicide. The best time to carry out this activity will be early in the crop life before crop plant root systems have started to utilise the inter-row space.

Other considerations

- Degradability timing appears to vary considerably depending on product thickness, region and climatic zone. On-farm experimentation may be required to identify the most suitable product brand and thickness.
- May be less suited to soil types where 'clodding' occurs, or stony soils. Both expose the mulch film to greater risk of tearing and more rapid break-down.
- Because they are designed to break down slowly through exposure to light during the life of the crop, rolls of biodegradable film should be stored in a dark, dry and cool location, and should be used within six months of purchase.
- Have been found to create a litter problem when used within vegetable production districts, with sections of film that have not yet broken down spreading around the district by wind and traffic.

Integration with other techniques

Biodegradable mulch films may allow some weeds to grow in the crop beds due to piercing of the mulch (deliberately for crop plants, or accidentally during laying or crop management). Research suggests this is more likely to be an issue than for conventional plastic mulches. Limited to extensive weed management may therefore be required within the crop beds (**hand weeding**, spot-spraying with **non-selective herbicide**), depending on success in managing the mulch to avoid piercing. Inter-row weed management will still be needed, including **shielded herbicide application** or **inter-row tillage**.

Techniques to *immediately precede* biodegradable mulch will focus on effective management of weeds in the fallow. This is likely to include **fallow and postharvest herbicides** (if registered for the crop), and **tillage** as well as **stale or false seed beds**.

These same techniques will also immediately follow plastic mulch removal after harvest.

Integration with other techniques will depend on farm circumstances (crops, soil and climate, staff, budget, and timing within crop cycle).

Maximising success

A fumigant (see 'Chemical fumigation') may be applied to the soil before the mulch is applied to increase the effectiveness of black plastic as a pest and disease control agent. Fumigation can also be an effective method of controlling weeds.

Extra caution will be required to minimise holes in the film layer. Avoid excessive foot traffic within crop beds, and lay the film with care.

Effective inter-row weed management will help reduce the weed seed bank.

Key references and further reading

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Limpus, S. 2012. Comparison of biodegradable mulch products to polyethylene in irrigated vegetable, tomato and melon crops. Sydney: Horticulture Australia Limited.

Cover crop mulches

In addition to being used as a weed suppression tool outside the normal cropping season (see 'Green manure and biofumigant cover crops'), certain cover crop types can also be used as a mulch substitute within a vegetable crop, potentially replacing plastic mulch films or reducing reliance on inter-row tillage and/or selective herbicide application.

Two types of cover crop mulches can be considered: 'living' and 'killed' mulch systems. Both will involve planting a cover crop before the cash crop, and then planting into the cover crop as a mulch.

In each case, the cover crop mulch is intended to suppress weed growth until the vegetable crop has covered the beds. Cover crop mulches also have a range of other potential benefits, discussed below. After the crop itself has covered the crop bed, the cover crop mulch becomes less important from the weed management point of view.

Careful management is critical to achieve the desired weed control aims. Poor cover crop establishment and maintenance, as well as inadequate termination of the finished cover crop, may lead to more weeds, and weed seed production.

Definitions

Cover crop mulches may be maintained as a **living mulch**, providing its growth is dormant during the cash crop growing season, or its growth can be stifled sufficiently so that it does not compete with the cash crop.

Alternatively, a **killed mulch** may be created by killing the cover crop to produce a mulch residue layer that effectively covers the crop bed and suppresses weed growth.

Advantages

- Living mulches can reduce weed populations to non-competitive levels, and improve the condition of the soil.
- They may have an allelopathic impact on weeds (for example, if cereal rye is used).
- They are more environmentally acceptable than standard plastic film systems (see 'Plastic mulch films').
- Improved soil structure, biological activity and nutrient cycling can be achieved through extended periods of vegetative ground cover, increased organic matter cycling and using nitrogen-fixing cover crops.
- They reduce the potential for wind and water erosion.
- They can reduce wind and soil contact damage to crops and crop fruit.

Disadvantages

- Living and killed mulches may provide insufficient weed control compared to conventional alternatives, or potentially shift the weed spectrum to biennial or perennial weeds if they are used over multiple growing seasons.
- They may also compete with the crop for nutrients, particularly if growing vigorously in comparison to the cash crop.
- They may have adverse impacts on vegetable crops (such as allelopathy, nutrient immobilisation, increased pest or disease activity and cooler soil temperatures).
- An increased cost will be incurred for ground preparation and planting through the cover crop, as well as opportunity costs of tying up resources in the mulch that could otherwise be used for cash cropping.
- Relatively advanced management skills, and potentially additional equipment, will be required to implement killed- and living-mulch systems.

Timing

The cover crop mulch will be established and managed in much the same way as a conventional green manure or cover crop (see 'Green manure and biofumigant cover crops').

Sufficient time should be allowed before the cash crop is due to be sown or planted for the cover crop mulch to establish as desired.

How to use

Planting into living or killed mulches can be carried out by direct drilling crop seed, however strip tillage (see 'Strip tillage') can also be used for either crop seed or transplants.

The potential for a living cover crop mulch to compete too vigorously with the cash crop may be managed by killing the mulch in a narrow strip along the planted row (Henderson 1998). Living mulches may also be managed by using low rates of selective herbicide to stifle growth without damaging the cash crop.

Killed cover crop mulches are usually terminated by applying a non-selective herbicide, waiting for the cover crop to die and then rolling it flat (for example using a crimping roller; Figure 3-31). In organic production, the crimping roller may be sufficient to terminate a living mulch for planting.

The vegetable crop is then planted into the stubble, usually with specialised planting equipment to cut through the killed mulch so that crop plants can be transplanted, or crop seed sown.

Figure 3-31. This crimping roller is used on an organic vegetable farm to prepare a killed mulch for the subsequent cash crop to be planted in to (Location: Gatton, Queensland).

Integration with other techniques

Both living and killed mulches may work well in combination with a **semi-permanent** (seasonal) crop bed system, integrated with **controlled traffic farming** (see 'Controlled traffic farming and reduced tillage').

Research suggests that **strip tillage** (see 'Strip tillage') using a living or killed mulch is a viable option for certain vegetable crops (for example, brassicas, cucurbits), with equivalent final crop yield.

Techniques to *immediately precede* cover crop mulches will focus on effective management of weeds in the fallow, as well as in prior cash crops. These techniques are likely to include **pre-emergent** and **post-emergent selective herbicides**, **fallow and postharvest herbicides** (if registered for the crop), **tillage**, **stale or false seed beds**, **thermal weeding** (particularly in organic production) and **hand weeding**.

Techniques to *immediately follow* a cover crop mulch (and harvest of the accompanying cash crop) may include **tillage** to incorporate of the crop residue, cover crop mulch and any weeds present. In the case of a living mulch, **non-selective herbicide** may be used to terminate the cover crop mulch and control any weeds present.

Integration with other techniques will depend on farm circumstances (crops, soil and climate, staff, budget, and timing within crop cycle).

Maximising success

Research suggests that it is good practice to ensure good weed control prior to sowing a cover crop mulch, either through cultivation of the crop beds, or herbicide application. This will apply immediately before establishing the cover crop mulch (a clean crop bed) but also in the longer-term so that the cover crop mulch is being established in a paddock with a relatively low weed seed bank.

This research implies that a cover crop mulch less likely to succeed in a paddock with a large weed seed bank, where large flushes of weeds may germinate immediately after the cover crop mulch is sown or planted, and impact negatively on the cash crop.

Nursery crops

Nursery crops are a cover crop species planted to support the growth of the cash crop during the early stages of its life cycle, by protecting it from adverse conditions (e.g. wind damage, soil abrasion and erosion; Figure 3-32).

Both the nursery crop and cash crop are sown simultaneously. Once the cash crop is established, the nursery crop is controlled using a selective herbicide, before it begins to compete with the cash crop for resources. Nursery crops are generally killed when relatively young. **This means that they are unlikely to have a weed management benefit within the cash crop**, other than by potentially helping the cash crop to establish more quickly and out-compete weeds germinating within the crop beds.

Figure 3-32. Wheat is being used as a nursery crop to support the growth of the carrot crop in this example in Myalup, Western Australia. The high winds common at the site make nursery cropping beneficial in restricting soil erosion and abrasion of the cash crop plants when young. The wheat plants will be terminated using a selective herbicide.

Key references and further reading

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Übelhör, A., Witte, I., Billen, N., Gruber, S., Hermann, W., Morhard, J., Claupein, W. 2014. Feasibility of strip-tillage for field grown vegetables. Journal Für Kulturpflanzen 66: 365-377.

Part 3E: Green manure and biofumigant cover crops

Planting a cover crop where the land may otherwise be left to fallow can suppress weed growth while delivering other benefits outside the cash crop season such as improved soil health and structure, enhanced organic matter, and reduced erosion.

Most vegetable growers who use cover crops therefore plant them for their soil health benefits, with weed management usually a secondary concern. Nonetheless, cover crops can be used effectively to suppress weeds to varying degrees depending on the cover crop species chosen, and how diligently the cover crop is managed. The benefits of weed suppression may carry over into the subsequent cash crop in the form of a reduced weed burden.

This section contains a range of summary information on the implications of cover cropping for weed management in vegetable production:

- The various advantages and disadvantages of cover cropping from the weed management point of view, including specifics to many cover crop varieties.
- General information on cover cropping as a weed management approach, including timing, variety selection, farm management considerations, integration with other techniques, and ways to maximise the success of the cover crop.
- Summary agronomic information on the main cover crop varieties that may be considered by vegetable growers, including climate suitability, soil preference, estimated time from sowing to incorporation, and whether each variety is considered to have a biofumigant effect.

Refer also to the poster 'Cover Crops for Australian Vegetable Growers' (AHR 2020) for summary information on choosing a suitable cover crop variety.

Advantages and disadvantages of cover cropping for weed management

In this section, information is presented on some of the key advantages and disadvantages of different cover crop varieties that are relevant to vegetable growers considering cover cropping as an approach to manage weeds in non-cash crop periods.

This information has been summarised from previous research on the effectiveness of cover crops in suppressing weeds, from Australia and elsewhere.

Advantages

Effective weed suppression due to dense canopy and/or high biomass. Cover crops which produce a dense canopy or high biomass have a competitive advantage over weeds by out-competing with the weeds for resources. Considerations include:

- A dense canopy with relatively high biomass may mean that the cover crop residue takes longer to break down after incorporation. This can extend the time required to include a cover crop in the crop rotation. Varieties with a dense canopy but relatively low biomass (e.g. buckwheat) may be preferable.
- Some varieties may produce a dense canopy but be relatively slow-growing, exposing them to weed infestation in the early stages. Combining dense canopy cover and rapid growth is preferable.

Quick growing cover crops. Varieties that germinate and grow quickly tend to be more effective in suppressing weeds. Early establishment gives these varieties a competitive advantage over weeds for light, moisture and nutrients. If they are also capable of forming a dense canopy, this will be established earlier in the crop cycle. Research suggests that quick growing cover crops, for example cereal rye, tillage radish or buckwheat, are less likely to have weeds present than some other varieties at the time of incorporation.

Relatively high cover crop canopies. Cover crops that produce a relatively high canopy (such as Caliente, forage sorghum or sunn hemp) have a competitive advantage over weeds due to their height. However, high seeding rates are likely to be necessary to ensure effective weed suppression, as taller stature cover crops may allow additional light to reach the soil surface and encourage weed germination, growth and seed production.

Competition with weeds for resources. Some cover crops may be capable of competing effectively with weeds for moisture and nutrients in particular, despite not necessarily producing a thick canopy. This is likely to be related to their high rate of growth, but may also be a feature of plant canopy structure.

Slashing and mulching cover crops at termination can be useful in producing a residual mulch that can allow continued weed suppression beyond the cover crop growing period. Sufficient time will be required in the crop cycle to make use of the cover crop mulch, so this approach may be suited to production cycles that usually include a relatively long fallow.

Some cover crop varieties show relatively **low susceptibility to insect, pest and disease pressure**. These varieties are worth consideration as low susceptibility will contribute to their vigour, and their ability to out-compete weeds.

Adaptability to moderate soils and climate extremes. Certain cover crops will grow vigorously despite relatively poor soils, or may succeed in either higher or lower temperatures, or in drought conditions.

Figure 3-33. Cover crops with a dense canopy can be very effective in suppressing weed germination and/or growth and seed set, by competing strongly for resources. These examples include a wheat cover crop near Gatton, Queensland; and a buckwheat cover crop trial near Hobart, Tasmania.

Disadvantages

Relatively poor weed suppression. Cover crop varieties that may be grown for their other benefits (such as improved soil health) may allow weeds to establish and succeed, particularly if they grow slowly or produce a sparse canopy.

Slow canopy establishment. Related to poor weed suppression, some cover crops have been noted to be relatively late in producing a canopy. In some cases however, these varieties may still produce a thick canopy before they are due for incorporation, and may still suppress weeds with some effectiveness.

High seeding rates. Research notes that certain cover crops should be sown at a high rate to ensure maximised weed suppression. However, this factor is likely to apply to all cover crop varieties.

Cover crops that are potential weeds. A number of cover crop varieties have been found to be potential weeds in their own right. Careful management of the cover crop can minimise this risk however, by ensuring the cover crop is terminated before seed is produced.

Herbicide resistance potential. In some cases, cover crops may be closely related to weeds known to have herbicide-resistant populations, or to be difficult to manage with herbicide, especially as mature plants.

Disease carryover into related cash crops. Where a cover crop is susceptible to disease, it has the potential to carry this over into subsequent cash crops. This is most relevant when the cover crop being considered, and the cash crop, are closely related.

Relatively long growing season. Cover crops that require a long growing season (e.g. over 100 days) are less likely to fit into a vegetable farm's annual crop rotation, although this will depend on location and seasonality of the cash crops grown.

Cash crop plant-back periods. Cover crops known to have a biofumigant effect (see 'Biofumigation and weed management') may require a plant-back period in between cover crop termination and incorporation, and sowing or transplanting of the next cash crop.

Persistent cover crop residue. Where cover crop plants are large and/or relatively 'woody', additional time may be required for plant residues to break down after incorporation into the soil. It may be possible to address this issue by incorporating the cover crop at a slightly earlier stage.

Unsuitability to climate extremes. As some cover crops are suited to extreme climates, others will be equally unsuited to these extremes. For details on climate suitability of each variety, please see Table 3-7 and Table 3-8.

Seed accessibility. Where a cover crop variety is relatively new to Australia, or is rarely grown either as a cover or cash crop, seed may be difficult to access. Ensure that seed may be sourced readily before committing to a particular variety.

Specific advantages and disadvantages of different cover crop varieties

The following pages provide a ready reference on the advantages and disadvantages of a range of commonly available cover crop varieties, with a particular focus on weed management.

Table 3-4 and 3-5 list specific advantages and disadvantages of cover cropping for weed management, with cover crop varieties noted within each.

More notes on the advantages and disadvantages of each cover crop variety is provided in Table 3-6.

This information has been compiled from available research on these cover crops. All advantages and disadvantages of each cover crop variety may vary depending on local climate and paddock management history, seasonal variation, and management of the cover crop.

In order to obtain the full benefit of a cover crop, it should be planted in its ideal growing season and provided with sufficient resources (water and soil nutrients) to establish and provide a thick canopy.

Table 3-4. Summary of the advantages of various cover crops for weed, crop and farm management (refer also to AHR et al., 2020).

	Dense canopy and/or high biomass	Grows quickly	Tall canopy/crop	Competes well for resources	Residue acts as an effective mulch	Short season	Low suscepti-bility to insect/disease pressure	Adaptable to moderate soils and climate extremes
Barley	✔	✔		✔				
Buckwheat	✔	✔				✔	✔	✔
Caliente						✔		
Canola	✔							
Cereal rye		✔		✔				✔
Corn			✔		✔			
Cowpea	✔	✔				✔		
Faba bean					✔			
Forage sorghum								✔
Italian ryegrass	✔	✔						
Japanese millet		✔						✔
Lablab	✔							✔
Lucerne								✔
Mung bean						✔		✔
Oats				✔		✔		
Sesame	✔							
Sunflower			✔			✔		
Sunn hemp			✔				✔	✔
Tillage radish	✔	✔						
Vetch							✔	✔
Wheat				✔				

Table 3-5. Summary of the disadvantages of various cover crops for weed, crop and farm management (refer also to AHR et al., 2020).

	Relatively poor weed suppression observed	Slow canopy establish-ment/ poor early weed competition	High seed-ing rate required	Cover crop is a potential weed	Cover crop has potential for herbicide resistance	Disease suscepti-bility and carryover into related cash crops	Relatively long growing season	Cash crop plant-back period (bio-fumigation)	Residue is persistent/ difficult to break down	Not suited to certain climate extremes	Seed may be difficult to access
Barley							✔				
Buckwheat				✔						✔	
Caliente	✔					✔		✔			
Canola							✔	✔			
Cereal rye				✔				✔	✔	✔	
Corn	✔		✔								
Cowpea						✔		✔			
Faba bean		✔				✔	✔			✔	
Field peas						✔	✔				
Forage sorghum		✔		✔				✔	✔	✔	
Italian ryegrass				✔	✔						
Japanese millet				✔							
Lablab	✔	✔				✔				✔	
Lucerne	✔	✔		✔	✔						
Lupins	✔	✔				✔	✔				
Mung bean			✔			✔					
Oats								✔			
Sesame							✔				✔
Snail medick	✔					✔				✔	
Soybean		✔				✔	✔				
Subterranean clover	✔			✔		✔					
Sunflower		✔									
Tillage radish						✔				✔	✔
Vetch	✔					✔		✔			
Wheat						✔				✔	

Table 3-6. Research results for the advantages and disadvantages of various cover crops for weed, crop and farm management.

	Advantages	**Disadvantages**
Barley	Grows quickly and produces a dense canopy to out-compete weeds. Early absorption of soil moisture also helps this cover crop to suppress weeds.	Up to 240 day growing season depending on variety and growing period; 90-120 days for summer varieties.
Buckwheat	Grows quickly and produces a thick canopy; capable of smothering weeds effectively due to competition, but may be less successful in competing with large weeds. Produces relatively low biomass despite thick canopy, allowing quick break-down of residue after incorporation. Growing season is only approximately 35-45 days depending on climate. Adaptable to soils of moderate fertility. Resistant to damage by insects and diseases.	Can self-seed and so crop must be terminated before seed set. Not suited to frost-prone regions or to warm, humid regions (e.g. northern Australia).
Caliente	Considered a relatively quick growing cover crop at 60-70 days in North America. Duration was about 100 days in WA trials.	Biofumigant effect on weed seed may be less effective than applying a conventional fumigation treatment. Marginal early season weed control noted. Will carry soil diseases over to brassica crops; not suited to brassica production system. ITCs considered less persistent than other biofumigant cover crops, reducing the plant-back period.
Canola	Produces high level of crop biomass and effective at smothering weeds. Incorporation of crop into the soil considered to reduce the emergence weeds due to allelopathy.	Winter growing season of approximately 120 days. Potential to injure subsequent vegetable crops due to allelopathic effect. Long plant-back likely to be required.
Cereal rye	Effective in out-competing winter annual weeds, and grows quickly to provide a thick canopy. May be even more effective if planted as part of a cover crop mix. Outperforms most cover crops on infertile soils. Winter hardy and drought-tolerant.	Can become a weed in its own right if not terminated before seed set. Requires a delay of up to four weeks after incorporation and before cash crop planting due to allelopathy. Especially relevant to small seeded vegetable crops such as carrots or onions. Late termination can result in excessive and persistent crop residue, and reduced soil moisture. Unlikely to suit northern Australian vegetable production due to higher temperatures.
Cowpea	Able to produce a canopy within 2-3 weeks of planting when planted in warm soil. Dense canopy effective in suppressing weed growth. 60-90 day growing season with good irrigation.	Not suited to rotations with nematode-susceptible vegetable crops. Some vegetable crops may be susceptible to allelopathic effects.

Table 3-6. Research results for the advantages and disadvantages of various cover crops for weed, crop and farm management (continued).

	Advantages	**Disadvantages**
Faba bean	Considered to suppress weeds when mulched layer left on the soil surface.	Relatively slow to form a canopy, allowing weeds greater chance of establishment. Not suited to rotations with nematode-susceptible vegetable crops. Has a long growing season. Susceptible to heat stress – not suited to northern Australian regions; prefers milder climates.
Field peas	Requires little irrigation to grow successfully.	Not suited to rotations with nematode-susceptible vegetable crops. 125 day growing season.
Forage sorghum	Quick to establish and effective in out-competing weeds when planted at higher rates. Grows well in hot climates.	Found to compete relatively poorly with weeds in some studies. Manage through slashing and early termination to ensure it does not produce seed. Residue (above-ground and roots) persistent and slow to break down. Requires up to two months plant-back period after termination/incorporation.
Italian ryegrass	Fast growing, produces high levels of biomass and found to be effective in out-competing weeds.	Closely related to annual ryegrass, a major weed of cropping in Australia that is sometimes used as a cover crop, and can be resistant to herbicides.
Japanese millet	Rapid growth rate allows it to suppress weeds effectively. Tolerant of dry conditions after establishment.	Reported to set seed quickly.
Lablab	Effectively smothers weeds once established. Tolerant of higher temperatures (option for northern Australia vegetable cover cropping).	Establishes slowly, therefore susceptible to weed competition in early growth stages. May produce less biomass than other cover crop options. Not suitable in rotation with nematode-susceptible vegetable crops. Hosts pests that are detrimental to beans. Intolerant of frost.
Lupins		Require considerable weed management when grown as a cash crop, so may not be effective in weed suppression as a cover crop. Not suited to rotations with nematode-susceptible vegetable crops. Susceptible to cucumber mosaic virus and may carry this over to subsequent cucurbit crops. Has a long growing season.
Mung bean	Only 70-80 days to maturity. Tolerant of hot and dry climates, and does not require much fertiliser input.	Plant at narrow spacing to facilitate effective weed smothering. Not suited to rotations with nematode-susceptible vegetable crops.

Table 3-6. Research results for the advantages and disadvantages of various cover crops for weed, crop and farm management (continued).

	Advantages	Disadvantages
Oats	Considered in one study to be more effective in weed suppression than vetch and clover. Requires only 70 days growing season.	Slow early growth. Three-week plant-back period after incorporation required, due to allelopathy.
Sesame	Research suggests it produces relatively high biomass compared to a range of other cover crops.	Approximately 120 day growing season. At the time of writing the industry in Australia had shrunk considerably, and seed may be difficult to access.
Snail medic		May suppress weeds less effectively than other cover crop options. Not suited to rotations with nematode-susceptible vegetable crops. Poor frost tolerance.
Soybean		May compete poorly with weeds during early life stages. May carry over diseases into subsequent bean crops. 100-140 day growing season.
Subterranean clover		Poor competition with and suppression of weeds found in overseas research. Potential to become a weed species if allowed to set seed. Not suited to rotations with nematode-susceptible vegetable crops.
Sunn hemp	High canopy suppresses weeds effectively. Adaptable to Australian climates from Tasmania through to northern production regions. Not susceptible to many pests or diseases. Beneficial effect on nematodes, relevant to following cash crops.	
Tillage radish	Effective suppression of autumn and winter annual weeds due to high biomass and rapid growth, and potentially allelopathic effect.	Weed suppression did not appear to extend into the following cash crop in one overseas study. Unlikely to suit northern Australian vegetable production due to higher temperatures. At the time of writing a relatively new variety in Australia, and seed may be difficult to access.
Vetch	Competes well with most weeds once established, particularly towards the end of its growing season. Tolerant of cold climates, including frost. Appears to reduce disease instances in following cash crops.	May suppress weeds less effectively than other cover crop options. Not suited to rotations with nematode-susceptible vegetable crops. Some vegetable crops may be susceptible to allelopathic effects of this cover crop.
Wheat	Competes well with most weeds once established, particularly towards the end of its growing season.	Somewhat more susceptible to disease than cereal rye or oats. Unlikely to suit northern Australian vegetable production due to higher temperatures.

The general characteristics of cover crops

Timing

Relevant to fallow periods in annual crop cycles. The growing period needs to be of suitable length to ensure the cover crop can grow vigorously to significant level of biomass through to incorporation.

Variety selection

- **Cereal cover crop varieties** often produce higher levels of biomass, but can require a longer growing season and may leave residues that take longer to break down in the soil.
- **Brassica cover crop varieties** are often chosen for their biofumigant effects on soil diseases and on weed seeds. However, their biofumigant effect can mean that there is a longer plant-back period for the following cash crop. They may also carry diseases into a following brassica cash crop. Selection of a non-brassica cover crop in a brassica production system builds a disease break into the annual crop rotation.
- **Legume cover crop varieties** are selected for their capacity to contribute to nitrogen fixation and improve soil fertility, however they may produce less biomass than cereal cover crops and some brassica cover crops.
- **Grass cover crop varieties** offer improvements for soil organic matter.
- **Cover crop mixes** may be appropriate depending on the farm system. They may deliver a particularly dense cover crop canopy and suppress weeds more effectively, providing the species within the mix do not compete overly with each other for resources.

Other considerations

The season in which a cover crop will be grown on your farm will depend on a range of factors, including:

- crop rotation plan (including allowing sufficient time in the rotation for the selected cover crop to grow to maturity and produce high biomass);
- climate (especially temperature and rainfall) in the available cover cropping window; and
- time to flower and/or incorporate (avoid cover crop seed production but maximise cover crop biomass).

Table 3-7 and Table 3-8 provide key characteristics for summer and winter cover crop varieties respectively.

Integration with other techniques

Non-selective herbicide, **pre-emergent herbicide** (if registered for the crop) and **tillage** may *immediately precede* cover crop establishment, to ensure a clean crop bed (similar to the process followed before sowing or planting a cash crop).

Selective herbicide application may also be used alongside cover crops, particularly cereal or grass varieties that may give an opportunity to apply herbicide for selective control of broadleaf weeds.

Techniques to *immediately follow* the cover crop will include those used to terminate and incorporate the crop (i.e. **non-selective herbicide** and **tillage**). Cover crop residues may then be left for a time sufficient to break down in the soil before the ground is prepared for the next cash crop.

Integration with other techniques will depend on farm circumstances (crops, soil and climate, staff, budget, and timing within crop cycle).

Maximising success

- **Sowing rate**: because the goal of cover cropping is not to harvest produce at the end of the cropping season, it is often appropriate to sow the crop at higher rates than would normally occur if planted as a cash crop, to maximise its weed suppression capacity.
- **Seed quality**: high quality, current-year seed should be sourced from a reputable supplier and stored appropriately before sowing. Choosing poor quality seed can result in patchy establishment and allow weeds to gain a greater foothold.
- **Soil characteristics**: variety selection will depend partly on the soil type and soil pH on your farm. Some cover crop varieties perform well in some soils and poorly in others, while other varieties tolerate a wide range of soils (see Table 3-7 and Table 3-8).
- **Crop management**: cover crops require sufficient attention to produce an appropriate amount of biomass. This may include sufficient irrigation, nutrition (e.g. fertilisers), insect pest management, weed management (e.g. pre-emergent herbicide).
- **Cover crop termination**: choosing to terminate the cover crop as late as possible before the cash crop is to be planted (using herbicide and/or tillage) can have weed management benefits within the following cash crop, and may reduce herbicide requirements elsewhere in the rotation.

Key references and further reading

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Summer cover crop varieties

Summer cover crops offer a short-season opportunity to improve the health of your soil and to suppress weeds during the warmest part of the year. Summer cover crops are likely to be suited to farms where the cash crop rotation may include a spring harvest and autumn planting, with a summer fallow.

Table 3-7 lists a number of cover crop species, some of which are suited to more temperate vegetable production zones in Australia while others are suited to sub-tropical and tropical production zones. Research publications and agricultural extension documents were reviewed and vegetable farmers and advisers consulted to develop this summary information.

Table 3-7. Summer cover crop options for the Australian vegetable industry: summary of key characteristics.

	Scientific Name	Category	Climate Suitability	Soil preference	Estimated time to flowering (termination), days	Biofumigant Effect?
Buckwheat	*Fagopyrum esculentum*	Pseudocereal	Frost intolerant. Sensitive to high temperatures (above 30°C), particularly where moisture is limited. Moist/cool temperate climate recommended for growth.	Performs best in moist but well-drained fertile soils, but grows well in low fertility soils. Tolerant of acid soils. Grows poorly on heavy limestone soils.	35-45	Yes
Corn	*Zea mays*	Cereal	Temperate climates (cold-intolerant); plant at soil temp 14-16°C.	Suited to deep, fertile loam soils and well-drained alluvial soils.	(70-100)	No
Cowpea	*Vigna unguiculata*	Legume	Heat tolerant and drought resistant. Highly adaptable. Tolerates annual mean temperatures ranging from 12.5°C to 27.8°C, and rainfall 280 mm to 4000 mm.	Does well on many soil types from highly acid to neutral, but less tolerant of alkaline soils. Grows best on sandy loams with good drainage. Soil pH 4.3 to 7.9	(60-90)	Yes

Table 3-7. Summer cover crop options for the Australian vegetable industry: summary of key characteristics (continued).

	Scientific Name	Category	Climate Suitability	Soil preference	Estimated time to flowering (termination), days	Biofumigant Effect?
Japanese millet	*Echinochloa esculenta*	Grass	Better suited to cooler climates.	Grows best in sandy-clay soils with pH value range of 4.6-7.4. Does not tolerate waterlogged soils.	60 (100)	No
Lablab	*Lablab purpureus*	Legume	Tolerates high temperatures. Grows best at average daily temperatures of 18-30°C. Drought tolerant once established. Frost susceptible. Rainfall of 750-2,500 mm preferred.	Light sandy soils through to well-drained but heavier textured/clay soils. Soil pH 4.5 to 7.5	(110-120)	Yes (possible)
Mung bean	*Vigna radiata*	Legume	Relatively drought tolerant. 600/1,000 mm annual rainfall range. Warm climates. Optimal temperatures are about 28-30°C.	Adapted to a wide range of well drained soils, but best on fertile sandy soils. Intolerant of waterlogging.	70-80	No
Sesame	*Sesamum indicum*	Oil-bearing	Adapted to hot dry climates. Grown in the warmer parts of Australia. Intolerant of frost.	Well drained sandy/ silty loam soils, pH 5.0 to 8.0 (7.0 recommended). Does not survive waterlogged or poorly drained soils or high salinity	40	Yes
Sorghum	*Sorghum sudanense; Sorghum bicolor*	Grass	Plant when soil temperatures exceed 15°C. Drought tolerance good. Rainfall of between 500 and 800 mm p.a. preferred.	Suitable for most soil types. Prefers good fertility and tolerates near-neutral to high pH soils (5.0 – 9.0), but tolerates low-fertility, moderate acidity and high alkalinity. Adapted on fertile soils from clay to loam. Poor tolerance of flooding.	(70-90)	Yes (possible)

Table 3-7. Summer cover crop options for the Australian vegetable industry: summary of key characteristics (continued).

	Scientific Name	**Category**	**Climate Suitability**	**Soil preference**	**Estimated time to flowering (termination), days**	**Biofumigant Effect?**
Soybean	*Glycine max*	Legume	Optimum growing conditions include mean temperatures ranging from 20°C to 30°C. Intolerant of prolonged sub-zero temperature exposure.	Moist alluvial soils with good organic content provide ideal growth conditions.	100-140	Yes
Sunflower	*Helianthus annuus*	Oil-bearing	Tolerant of dry conditions and frost. Soil temperature of 10-12°C for sowing. Less successful when air temperatures exceed 40°C.	Prefers well drained soils, and tolerant of clay loam, silty clay and sandy loam soil types. Intolerant of acidic soils pH 5.0 or less.	55-100	Yes (possible)
Sunn Hemp	*Crotolaria juncea*	Legume	August-December sowing time suggested in southern Australia. Grows all year round in northern Australia. Frost intolerant. Mean annual temperature 9-30°C, mean annual rainfall 170-1500 mm.	Widely adaptable to different soil types. Less tolerant of high alkaline soils. Soil pH 4.5 to 8.5 acceptable.	(130-150)	Yes

Winter cover crop varieties

Winter cover crops are usually planted in autumn and allowed to grow until spring, when they may be terminated by herbicide application or by tillage.

Selection of cover crop species will be influenced by local climate. Some of the species listed in the table below require relatively warm temperatures for germination, and so will need to be planted in early autumn depending on local climate. Others are not adapted to dry winters or to frost.

Again, research publications and agricultural extension documents were reviewed and vegetable farmers and advisers consulted to develop this summary information.

Table 3-8. Winter cover crop options for the Australian vegetable industry: summary of key characteristics.

	Scientific Name	**Category**	**Climate Suitability**	**Soil preference**	**Estimated time to flowering (termination), days**	**Biofumigant Effect?**
Barley	*Hordeum vulgare*	Cereal	Frost intolerant. 4°C minimum required for germination. Optimum germination temperature 20°C, maximum 28-30°C. Drought tolerant.	Intolerant of waterlogging, does poorly in heavy soils. Grows poorly in soils with pH less than 5.5.	(100-150)	Yes
Canola	*Brassica napus*	Brassica	Optimum soil temperature range for germination of 15°C to 20°C. Rainfall of approximately 300 mm minimum.	Adaptable but best soil types are red-brown and clay soils. Will succeed in sandy soils.	150-210	Yes
Cereal rye/ Ryecorn	*Secale cereale*	Cereal	Suited to cooler climates and grows well in dry conditions.	Best in light loams and sandy soils. Tolerant of acid, dry soils and heavy clays. Soil pH 4.5 to 8.0.	(90-180)	Yes

Table 3-8. Winter cover crop options for the Australian vegetable industry: summary of key characteristics (continued).

	Scientific Name	Category	Climate Suitability	Soil preference	Estimated time to flowering (termination), days	Biofumigant Effect?
Faba bean	*Vicia faba*	Legume	Best suited to temperate parts of Australia. Able to tolerate frost during vegetative stages. Develops rapidly when daytime temperatures reach 15-25°C. Intolerant of drought and heat.	Grows on a wide range of soils from loams to clays and under various draining conditions, but intolerant of water logging. Soil pH 4.5 to 8.3	(130-220)	Yes
Field peas	*Pisum sativum*	Legume	Soil temperatures of 7-8°C required for germination. Intolerant of drought. 400 mm annual rainfall.	Sandy or medium-loam, moderately fertile and well-draining soils. Tolerates pH 4.5 – 8.5.	-125	No
Indian Mustard 'Caliente'	*Brassica juncea*	Brassica	Suitable across Australia, e.g. Tasmania and Western Australia. Sufficient soil moisture required for quick germination.	Soil pH above 5.5 for best results.	(60-70)	Yes
Lupins	*Lupinus* spp.	Legume	Prefers moderate temperatures and rainfall. Frost intolerant. Intolerant of higher temperatures (> 30°C).	Suited to sandy/coarse acid to neutral soils. Good draining soils best. Intolerant of waterlogging. Soil pH 4.5 to 7.	(180-300)	No
Oats	*Avena sativa*	Cereal	Tolerant of light frosts.	Adapted to moderately fertile soils from sands to clays. Soil pH 4.5 to 8.5.	(40-70)	Yes
Ryegrass	*Lolium* spp.	Grass	Ideally receives a large autumn/winter rain event to facilitate germination. Requires large amounts of water and nitrogen. Intolerant of drought.	Prefers heavy clay or silty soils with adequate drainage. Will grow well on sandy soils if well fertilised. Tolerates temporary flooding.	(150-180)	No

Table 3-8. Winter cover crop options for the Australian vegetable industry: summary of key characteristics (continued).

	Scientific Name	Category	Climate Suitability	Soil preference	Estimated time to flowering (termination), days	Biofumigant Effect?
Snail medic	*Medicago scutellata*	Legume	Temperatures in the range of 11.5°C to 26.2°C tolerated. Rainfall of between 350 and 800 mm p.a. tolerated. Poor frost resistance.	Thrives in most soil types, especially heavy and loamy soils, but susceptible to water logging.	Not identified	No
Subterranean clover	*Trifolium subterrane-um*	Legume	A winter annual in Mediterranean climates. Widely grown in southern Australia; annual rainfall range 350 - 1200 mm.	Sandy loam to clay; acid to neutral soils preferred. Soil pH range requirements of 5.0 to 10.5, but most productive in a pH range of 6.0 to 7.0.	80-120	Yes (possible)
Tillage radish	*Raphanus sativa*	Brassica	Tolerates light frosts down to -4°C. Min. soil temperature for germination 7°C.	Intolerant of wet soils. Able to grow in heavily compacted soils.	-60	Yes (possible)
Vetch	*Vicia villosa*	Legume	Has been successfully grown in average temperatures ranging from 8.4°C to 19.4°C. Grown in areas of annual rainfall 350-1000 mm. Some drought tolerance, does not tolerate water logging.	Adapted to well drained sandy to heavy clay soils with pH from 5.0 to 8.0. Performs best in near neutral soils. Some salt tolerance.	260-300	Yes
Wheat	*Triticum* spp.	Cereal	Adapted to range of climates. Tolerates temperatures from 4.9 to 27.8°C. Hot and humid conditions are unfavourable for wheat growing. Minimum germination temperatures between 3 and 4°C.	Prefers well-drained fertile soils but tolerant of heavy, poorly drained soils. Soil pH 4.5 to 8.3.	(120-150)	No
White mustard	*Sinapis alba*	Brassica	Mediterranean climate (avg. temp. range of 10 to 25°C).	Adapts to a range of soil types.	(60-80)	Yes

Biofumigation and weed management

What it is and how it works

Biofumigant crops such as *Brassica* species or some sorghums contain naturally occurring glucosinolates (GSLs), which contribute to the biofumigant effect. When a biofumigant crop is incorporated into the soil, GSLs are broken down into isothiocyanates (ITCs), which are toxic to many soil-borne pests and diseases.

Biofumigation is known to provide benefits with regard to soil-borne disease management, and is increasingly being used by Australian vegetable growers, primarily for this reason.

Figure 3-34. A range of biofumigant cover crops are available, many of which are in the brassica or mustard families. Here, Caliente (Brassica juncea) *is being grown at a research site near Forthside, Tasmania*

Relevance of biofumigation to weed management

Certain biofumigant cover crop species may also be capable of reducing the impact of weeds in vegetable crops, and the weed seed bank, due to biofumigation. ITCs have been shown in experimental conditions to inhibit weed seedling growth or prevent seed germination.

In addition to brassicas and mustards, some legumes (for example faba bean, cowpea and vetch) and cereals such as oats, have also had demonstrated biofumigant effects, including on weed germination and growth.

However, research suggests that the specific effect of biofumigation on weeds, rather than plant competition, in the field is not always found. The ability of biofumigant crops to suppress weeds by out-competing with them for resources may potentially be as important, or more important, than a biofumigant effect.

Cover crop varieties which are considered to have a biofumigant effect are noted in Table 3-7 and Table 3-8 above.

Factors influencing effectiveness

- **Soil and climatic conditions** appear to influence the production and retention of ITCs. Factors maximising the biofumigant effect may include neutral soil pH, higher soil temperatures (e.g. >25 degrees Celsius in the case of *Brassica juncea*) and high moisture content. Less effective in soils with a history of chemical fumigation, or high organic matter content.
- **Effective management of the biofumigant cover crop** can influence final ITC levels. This includes providing sufficient fertiliser and irrigation, and timing incorporation appropriately with regard to crop growth stage, soil condition and climate.
- **Incorporation method** influences biofumigation effectiveness for example, finely chopping the cover crop biomass and incorporating it immediately may hasten their effect.
- **Sealing the soil surface** through irrigation, rainfall or rolling the paddock also enhances the performance of ITCs. **Covered soils** (e.g. with a plastic mulch film) also retain ITCs more effectively and may help deplete the weed seed bank, although this approach is relatively impractical and expensive.
- **High levels of biomass production** improve the capacity of biofumigant cover crops to suppress weeds, and potentially to deplete the weed seed bank.
- Weed seed buried **closer to the soil surface** may be more susceptible to biofumigant effects.
- Weed seed from smaller-seeded species (e.g. chickweed, *Stellaria media*, or amaranth, *Amaranthus retroflexus*) may also be more susceptible to biofumigant effects than somewhat larger-seeded weed species (e.g. fat hen, *Chenopodium album*, or blackberry nightshade, *Solanum nigrum*).
- Similarly, weed seed with a softer seed coating may be more susceptible to biofumigant effects than weed species with a harder and less penetrable seed coat.

While it is reasonably likely to have positive effects on the health of the soil, biofumigation may or may not help to manage your weed load, depending on the factors outlined above.

However some Australian vegetable growers have found considerable success in using biofumigant cover crop types to suppress weeds on their farm, and the approach is worth consideration as part of your IWM strategy.

Other considerations

Research suggests that biofumigant effects can vary depending on conditions and circumstances. For example, in the case of 'Caliente' (*Brassica juncea*), some studies have shown notable reductions in post-incorporation weed emergence, while others have identified similar weed pressures to other cover crops.

It is worth being cautious about the selection and use of a biofumigant cover crop, since the biofumigant effect may also reduce the growth and yield of the following cash crop. For example, smaller seeded cash crops may be susceptible to damage from biofumigation depending on the time allowed between incorporation of the cover crop, and sowing the cash crop.

Certain combinations of cash crop and biofumigant cover crop may also be unsuitable, for example growing *Brassica* cash crops and cover crops in the rotation may risk carrying over diseases that impact the cash crop.

It is worthwhile seeking the advice of your agronomist or advisor before considering a cover crop species that is reported to have a biofumigant effect. On-farm trials and consultation with other nearby growers who have used biofumigation may also provide important local information on management and effectiveness.

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Farm management is complex, and vegetable growers are required to implement an overall management strategy which will have a variety of goals, with effective weed management only one of these.

A range of crop agronomy practices can be implemented for multiple farm management reasons, but these practices still have positive implications for weed management. These may include:

- Paddock history and planning.
- Crop rotation.
- Competitiveness and vigour of cash and cover crops.
- Irrigation management strategies.

Paddock history and planning

Advantages

- Knowing the weeds present across the farm, and their relationship to crops grown, can help target and improve an IWM strategy.
- Producing farm weed maps helps to visualise weed problems and contrast these to annual cropping cycles and forward plans. This can assist with crop site selection and rotation plans, and weed management windows (e.g. during crop fallow) that together may be used to reduce weed impacts.

Timing

A continual farm management process.

Useful information on weeds present on-farm

- how they impact on the crops commonly grown;
- whether their effect is greater (and management more difficult) in some crops compared to others;
- which tactics have been most effective at managing weeds in different crops;
- which parts of the farm you usually find them on;
- how severe the infestation tends to be on different parts of the farm;
- what time/s of year they germinate, grow and produce seed;
- whether these weeds can reproduce via seed only, from plant parts, or both;
- how long the weed seeds can remain viable in the soil; and
- at what depth in the soil the weed seed is capable of germinating.

Key references and further reading

Integrated weed management guides are available for eleven of the most common and problematic weeds of vegetable production in Australia:

- Amaranth (*Amaranthus* spp.).
- Blackberry nightshade (*Solanum nigrum*).
- Chickweed (*Stellaria media*).
- Common sowthistle (*Sonchus oleraceus*).
- Dwarf nettle (*Urtica urens*).
- Fat hen (*Chenopodium album*).
- Marshmallow (*Malva parviflora*).
- Nutgrass (*Cyperus rotundus*).
- Pigweed (*Portulaca oleracea*).
- Potato weed (*Galinsoga parviflora*).
- Wild radish (*Raphanus raphanistrum*).

The Soil Wealth and Integrated Crop Protection web pages (https://www.soilwealth.com.au/) and CABI Invasive Species Compendium (https://www.cabi.org/isc/) are also useful sources of information on specific weed species.

Crop rotation

A diverse crop rotation can be used to vary the growing environment weeds experience. This can reduce the diversity and abundance of weeds, 'keeping the weeds guessing' through variable timing of crop establishment, management, harvest and residue incorporation activity. A complex crop rotation makes it possible to manage priority weed species with greater effect.

Advantages

Diverse crop rotation is a useful weed management tool for controlling many broadleaf species on a farm where vegetables are grown.

- Continuously planting a single crop or family of crops, or maintaining an annual crop cycle without variation over time, can eventually select for particular weeds which may be difficult to control within these crops.
- Establishing a more diverse crop rotation may provide an opportunity to rotate herbicides, and use different herbicide groups to manage a wider spectrum of weeds (see 'Herbicide resistance').
- The mix and timing of other weed management practices will also change across a diverse crop rotation, in response to each crop's requirements. This will make the growing environment less predictable for weeds and other pests and diseases.

Disadvantages

- Diverse rotations may not be feasible on farms in the peri-urban fringes of Australia's major cities, where production on small parcels of high-value land must often focus on the highest value crops.
- Rotation to non-vegetable crops (such as sugarcane or pasture) may require access to different planting and harvesting equipment, access to markets, and knowledge and skills.
- Rotation alternatives may not be as suited to the local climate and conditions, or fit as well into the remainder of the crop production cycle, as the 'standard' established rotation.

How to use

The type of crop rotation adopted will vary from farm to farm, and across seasons.

A successful crop rotation for weed management will involve changes between crops, for example: seasonal variations in sowing/transplanting and harvest dates; variation in growth habit and competitive ability of crops; availability of diverse in-crop weed management options across the rotation (herbicide and other); and variation in crop management and fertiliser application. Including cover crops and fallow periods in the rotation can provide additional benefits in weed suppression or control, and provide other benefits to the farm. Commonly, this may entail switching between closely related crops in a particular family, e.g. brassicas, cucurbits.

A diverse and seasonally adjusted crop rotation maximises the possibilities for variation, meaning that particular weed species are less likely to dominate over time as their growing environment becomes less predictable. This particularly applies to weeds with a relatively long growing period, from germination to seed production.

However, in a more complex rotation, quick-maturing annual broadleaf and grass weeds may have a greater opportunity to dominate.

This means that planning a crop rotation with weed management in mind requires good knowledge of weed ecology (including weed species dominant in the field, their lifecycle and behaviour), weed mapping and paddock history (see 'Paddock history and planning').

Timing

A continual farm management process. May include cover crops and stale or false seed beds depending on available time in the rotation.

Examples

A variety of rotation possibilities are practised across Australian vegetable farms. The goal should always be to reduce the number of weeds producing seed, consequently depleting the weed seed bank over time. Some examples include:

- Rotating cucurbit production with sugar cane production in central Queensland to allow broadleaf-selective herbicides to be used within the sugar cane, potentially reducing the impact of these weeds in subsequent cucurbit crops.
- Rotating amongst different broadleaf vegetable crops that allow use of different selective herbicides in Tasmania, to manage glyphosate resistant ryegrass (*Lolium rigidum*).
- Including brassica crops in a lettuce rotation in south-east Queensland to allow use of different herbicides at transplant, reducing the incidence of potato weed (*Galinsoga parviflora*) in subsequent lettuce crops.
- Including some quick-growing crops in the rotation (for example, babyleaf varieties), where weeds may not have a chance to produce seed until post-harvest weed control is undertaken.
- Including a fallow in the rotation, or increasing the length of the fallow somewhat will allow a stale or false seed bed to be implemented to help deplete the weed seed bank - see 'Stale and false seed beds'.
- Rotation to a non-cash cover crop can present potential benefits outside of herbicide rotation in the areas of weed suppression and biofumigation, and is discussed further in 'Part 3E Green manure and biofumigant cover crops'.

Key references and further reading

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Smith, R.F., Shaw-Parker, J. 2014. Evaluation of the impact of organic weed control practices on soil seed banks of organic farms in California, USA, in Cloutier, D.C. (Ed) 10th EWRS Workshop on Physical and Cultural Weed Control. Alnarp: European Weed Research Society.

Crop competition

Crop competition means ensuring that vegetable crop competiveness is maximised compared to the weed. Good early crop growth and a thick crop canopy helps to give the crop a competitive advantage over weeds (Figure 3-35). Generally, weeds are a less significant problem once the crop canopy closes fully, however this is not relevant to all crops, some of which are naturally short (e.g. onions, Figure 3-36) and retain an open canopy until harvest (e.g. carrots).

Where it is possible for a vegetable crop to compete effectively with weeds, a range of agronomic strategies can be considered to maximise crop competitiveness. These are summarised below.

Figure 3-35. Maintaining a thick crop canopy can help suppress weed growth, following up from pre-plant or pre-sow weed management activities (Location: Gin gin, Western Australia).

Figure 3-36. Onions are particularly susceptible to weed invasion due to lack of a crop canopy, such as this crop which is heavily invested with nutgrass (Cyperus rotundus) (Location: Lockyer Valley, Queensland).

Advantages

- Weeds are unlikely to penetrate a fast growing crop with a thick canopy and compete with the crop, reducing their impact on crop yield.
- Broadleaf weeds germinating several weeks after a vegetable crop with a thick canopy has been planted have little impact on final crop yield. That is because by this stage in the crop life cycle, the weeds are unable to penetrate the canopy and compete effectively with the crop.
- Maintaining a competitive crop will result in fewer and shorter weed plants, and ultimately reduced seed production and less return of weed seed to the soil.

Disadvantages

- Not relevant to all vegetable crops. Where the crop canopy takes longer to close, or may never close fully, it is likely that weeds will need to be managed within the crops rows throughout the life of the crop.
- Improving crop competitiveness by increasing planting or sowing density may reduce overall crop yield, by placing crop plants in a situation where they compete with each other for resources.

Timing

Managing the cash crop to maximise its competitiveness with weeds is a continual process, within the crop cycle itself but also during other cash crop periods, fallows, and when cover crops are growing.

Maximising success

- Maintain **ideal soil conditions**, including application of fertiliser and irrigation when needed.
- Ensuring that the **weed seed bank within the soil** is well managed, using any tactics described in this Manual relevant to the crops in question (Figure 3-37).
- Choosing where possible to grow the **most competitive types of cash crop** in the annual rotation, which will form a thick canopy and out-compete weeds. This may be especially relevant on farms that have a high weed seed bank present within the soil, and may require the grower to reconsider growing crop types which are likely to form a relatively open canopy, such as carrots or onions.
- Similarly, choosing the **most competitive crop variety** within a particular type of crop. This will take local conditions and experience trialling different varieties into account.
- Adjusting **plant spacing** by using a **higher planting or sowing density** (that is, number of plants or seed per square metre) may allow the crop canopy to fully cover the crop beds earlier in the crop life.
- Where crops are sown rather than transplanted, using the **optimum sowing depth** will maximise the ability of the crop to out-compete weeds by giving the crop every chance of establishing well.
- Using the **optimum sowing time** to maximise the crop's early growth rate will also maximise its chance of out-competing weeds that are germinating in the crop beds at the same time, through vigorous crop canopy establishment.
- **Changing crop orientation** has the potential to reduce the weed burden through more effective shading of the paddock, and is particularly relevant to wheel tracks (see 'Box 1: The potential weed management benefits of changing crop orientation').

Figure 3-37. Lack of a crop canopy makes certain crop varieties highly susceptible to weed infestation if diligent weed management is not undertaken, as this infested celery crop illustrates (Location: Adelaide, South Australia).

Other considerations

Where the weed burden is especially heavy, it may be more beneficial to delay sowing and carry out additional fallow weed management, than to rely on a crop being able to out-compete weeds.

Where possible, plant crops in paddocks that have a good history of weed control. This will significantly reduce the weed burden on the crop through a much reduced weed seed bank.

Integration with other techniques

Crop competitiveness will be maximised by sowing or planting the crop into a clean, weed-free crop bed that has a history of effective weed management. All **pre-plant or pre-sow weed management techniques** described in this Manual are worth consideration, depending on the crop.

Within the crop itself, effective intro-row weed management soon after germination or transplanting are also likely to enhance crop competitiveness. Consider **inter-row tillage**, **post-emergence or post-plant selective herbicides** (if registered for the crop), **hand weeding**, or potentially selective **thermal weeding**.

Following harvest, effective management of weeds in the crop residue, and cleaning up the beds as soon as possible, will help keep the weed seed bank down, and contribute to the competitiveness of the next cash crop.

Integration with other techniques will depend on farm circumstances (crops, soil and climate, staff, budget, and timing within crop cycle).

Key references and further reading

Borger, C.P.D., Hashem, A., Pathan, S. 2010. Manipulating crop row orientation to suppress weeds and increase crop yield. Weed Science 58: 174-178.

Henderson, C.W. and A.C. Bishop. 2000. Vegetable Weed Management Systems, pp. 355-372 in Sindel, B.M. (Ed) Australian weed management systems. Meredith: R.G. and F.J. Richardson.

Masiunas, J.B. 2008. Weed control for commercial vegetable crops, pp. 157-192 in Bissonnette, S., Overmier, M. (Eds) 2008 Illinois agricultural pest management handbook. Urbana-Champaign: University of Illinois.

Box 1: The potential weed management benefits of changing crop orientation

Depending on paddock layout (shape and size, prevailing slope and drainage), it may be possible to consider planting the crop on an east-west orientation rather than a north-south orientation. Research in the grains industry suggests that east-west oriented crops are more likely to shade the inter-row space (space in between the crop lines on the raised crop bed, as well as the wheel tracks), and make it more difficult for weeds to establish, grow and produce seed in this part of the paddock than may be possible in open sunlight (Borger, Hashem, & Pathan, 2010). In vegetables, this may similarly be the case in reducing weed competition directly within the crop beds, and in the longer term reducing the weed seed bank.

As an approach to managing weeds, crop orientation is more likely to be effective in southern Australia, particularly in winter where the lower angle of the sun in the sky means that the crop bed inter-row spaces will be shaded for a larger part of the day.

Other considerations include: whether the weed species present are still likely to grow well in shaded conditions; and whether east-west orientation means that crop plants may out-shade each other to some extent within the crop rows, potentially reducing final crop yield compared to a paddock planted on the north-south axis.

Irrigation management

Sufficient moisture availability is important to weed germination and growth. This means that the frequent irrigation activities common to vegetable production create conditions that are favourable to weeds. Most vegetable farms use either solid set or centre pivot overhead irrigation systems, though in crops where plastic mulch films are used, drip irrigation will be used. Various adaptations can be made to irrigation approaches to help reduce the impact of weeds.

Figure 3-38. In this crop, drip irrigation was used to restrict the amount of soil moisture between the crop rows, both to reduce irrigation water use and to reduce inter-row weed germination (Location: Richmond, New South Wales).

Pre-irrigation to stimulate a flush of weed growth

Before the crop is planted or sown, irrigate the formed crop beds to stimulate weed growth. These can then be controlled either by non-selective herbicide application or shallow tillage. This is also known as the **stale or false seed be**d approach (see 'Stale and false seed beds'), and pre-irrigation is central to its effectiveness by maximising the number of weeds that germinate.

Consider utilising drip irrigation

Some Australian vegetable growers have used **surface-level drip irrigation** in vegetable crops rather than the more commonly used flood or spray irrigation. By keeping the wheel tracks relatively free of moisture, weed germination and growth may be restricted.

Another key advantage of this approach is water use efficiency. However, a potential disadvantage is the time and expense required to establish drip irrigation systems within every crop, and remove the infrastructure post-harvest.

Subsurface drip irrigation has been shown in a number of studies overseas to result in significant reductions in the weed burden in vegetable crops, as it targets the subsurface root structures of crops and leaves the soil surface (from where many weed seed may germinate) relatively dry.

It also has the advantage that the irrigation tubing/tape can be laid at a depth below the tillage 'zone', allowing infrastructure to remain in place for several crop seasons. However, this will be associated with significant setup costs and additional ongoing management requirements.

Drip irrigation systems are less likely to reduce the weed burden in humid vegetable production zones, where regular rainfall will ensure sufficient soil moisture is available to grow weeds regardless of the drip irrigation system.

Irrigation to improve herbicide effectiveness

Many herbicides are most effective in moist soils, and some weed escapes can be expected in dry conditions. Weeds that are not suffering from moisture stress will be more easily controlled using herbicides.

Where dry weather threatens to reduce the effectiveness of herbicide application, growers may consider irrigating the paddock before the herbicide is applied – or after application, depending on the product being used. Always read the herbicide label closely to determine the relationship between effectiveness and soil moisture level.

Although an additional irrigation may be expensive in time and resources (or not possible during drought), it is likely to deliver longer-term benefits through a reduced weed burden in future crops.

Key references and further reading

Coolong, T. 2013. Using Irrigation to Manage Weeds: A Focus on Drip Irrigation, pp. 161-179 in Soloneski, S., Larramendy, M. (Eds) Weed and pest control: conventional and new challenges. Rijeka: inTech.

Lamont, W.J., Orzolek, M.D., Harper, J.K., Kime, L.F., Jarrett, A.R. 2012. Drip Irrigation for Vegetable Production. Available at https://extension.psu.edu/drip-irrigation-for-vegetable-production. Accessed 5th May, 2021.

Farm hygiene

Figure 3-39. The Loose Leaf Lettuce Company in Gingin, WA enforces a strict farm hygiene strategy, including restrictions on people and vehicles allowed on the farm, and requiring visitors to report to the office.

Farm hygiene practices can be used to successfully limit the spread of weeds across and between properties, by restricting the movement of weed seeds and weed plant parts that may be capable of taking root if spread elsewhere. In contrast, poor hygiene practices can allow weed infestations to take hold on farms (or paddocks) that were previously relatively weed free.

All weed management methods that are part of IWM contribute to farm hygiene, as their goal is to prevent production of weed seed, to reduce the burden of weeds over time. However farm hygiene principles include more than just direct weed control.

Diligence is key to successful farm hygiene. By planning a farm hygiene strategy and following it diligently over time, the other weed control methods implemented as part of an IWM strategy are given a greater chance of success.

Advantages

- Isolate weed outbreaks to specific parts of the farm, or potentially minimising the risk of new and important weeds making their way onto the farm.
- Support IWM strategy by restricting weed spread and reinfestation. Longer-term success is likely if implemented diligently.
- Unlikely to require specialised equipment or expertise – easy to implement.
- Many of the practices also help reduce the risk of plant diseases or insect pests impacting on crops.

Disadvantages

- Additional field staff time required to ensure diligent hygiene is applied.
- Staff diligence and motivation may be inconsistent.
- It may take several seasons for the benefits to become apparent, as the weed seed bank is depleted.

Figure 3-40. Permanent wash-down bays on the farm provide a single location where growers can clean and disinfect their farm machinery to minimise the risk of weed spread, as well as restrict spread of pests and diseases. Weed seed germinating around the wash-down bay as a result of cleaning activity should be controlled using a knock-down herbicide to ensure they do not spread back into the cropped areas (Location: Myalup, Western Australia).

Timing

A continual farm management process. **Diligence** is the key to success.

Farm hygiene principles for weed management

Weed management in non-cropping areas and during crop fallows

- Control weeds in areas near paddocks such as fence lines, around buildings and infrastructure (Figure 3-41). Use **non-selective herbicide**.
- Ensure that weeds are suppressed or managed diligently during crop fallow periods, before they produce seed. Relevant approaches may include **non-selective herbicide**, **tillage**, **stale or false seedbeds**, **cover crops**, or a combination of these approaches as appropriate.

Figure 3-41. Fence line and farm infrastructure are significant sources of weed reinfestation in surrounding vegetable crops. In the photo on the left, the proximity of the weed infestation to the crop suggests that control may involve applying a non-selective herbicide only after the crop has been harvested (to avoid spray drift damage to the crop), or during fallow periods in the annual production cycle. In the photo on the right, non-selective herbicide may also be used to manage weeds around farm buildings before they produce seed (Location: left - Devonport, Tasmania; right - Adelaide, South Australia).

Minimise weed seed production

- Reduce the number of weeds producing seed (either within a cash crop, a fallow paddock or non-crop areas) to minimise contributions to the weed seed bank, and future weed problems.
- Timely application of weed control is key.
- Follow-up control of mature weeds using **herbicide** or by **hand weeding**.
- Remove weeds from site, particularly if seed has been produced or if the plant is capable of re-rooting.
- Read more in the case study 'Diligent hand weeding ultimately pays off'.

Post-harvest weed management

Even in crops managed very effectively for weeds, at least some weeds are likely to be present at the time of harvest.

- Manage weeds within the post-harvest crop residue as soon as practical, to avoid weed seed production in post-harvest paddocks.
- Relevant control approaches include **tillage** and **non-selective herbicide**, or perhaps a mixture of both.

Equipment wash-down

- Establish a set wash-down area or facility, and ensure that all machinery and vehicles are cleaned thoroughly prior to on-farm activities, and when leaving the farm (Figure 3-40).
- Especially relevant to contractor and visitor vehicles and machinery.
- Washing down on-farm machinery can help restrict weed spread from one part of the farm to another.

Footwear and clothing

- Provide wash-down facilities for boots, ensure that boots are free of soil and plant material before staff, contractors and visitors enter and leave the farm.
- Monitor clothing of staff and visitors, as seed of some weed species can adhere to clothing.

Restrict vehicle and people movement on-farm

- Maintain set vehicle tracks and laneways to restrict machinery and vehicle movement across paddocks.
- Manage these laneways diligently for weeds, e.g. using non-selective herbicide; or maintain good ground cover on laneways.
- Establishing set drop-off and pick-up points for farm deliveries and produce, and designated parking areas.
- Restrict visitor access to paddocks; ensure visitors use footwear washdown and are not carrying weed seed on their clothing.
- Make all visitors and staff aware of the risk of weed spread. Casual staff are a particular risk, especially those moving from one farm to the next.
- Signage can be used to remind visitors and staff to remain diligent, and should be placed prominently (Figure 3-39).

Staff training and motivation

- Provide all field staff training in weed identification and in relevant hygiene practices.
- Motivate staff to prioritise weed removal (before seed set if possible) at all stages of the crop, during all field activities, and in adjacent non-crop areas.
- Ensure that staff understand the eventual benefits of maintaining strict farm hygiene practices, with a goal of restricting weed seed set.
- Read more in the case study 'Diligent hand weeding ultimately pays off'.

Use low-risk farm inputs

Many farm inputs carry a potential weed spread risk.

- Be aware of the weed seed contamination risk of organic mulches, as well as unprocessed fertilisers such as animal manure. Consider suitably processed or composted mulches and fertilisers (Figure 3-42).
- Purchase certified crop seed and seedlings to reduce the risk of weed seed contamination.
- Closely observe paddock sites where inputs have been applied for unusual weed outbreaks. Control outbreaks diligently to avoid seed production.

Figure 3-42. Organic mulch use in the Australian vegetable industry is relatively uncommon, but where growers do use it they should remain aware that it has the potential to spread weeds onto their paddocks (Location: Bundaberg, Queensland).

Key references and further reading

Plant Health Australia and Animal Health Australia have contributed to the Farm Biosecurity web site, which includes a range of useful manuals and planning documents explaining the principles of effective farm hygiene in more detail. http://www.farmbiosecurity.com.au

Coleman, M., Kristiansen, P., Fyfe, C., Sindel, B. 2019. Effective Integrated Weed Management - Case Study: Diligent hand weeding ultimately pays off. Armidale: University of New England.

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Part 3G: Thermal weed control

Soil solarisation is a form of thermal weed seed management in which solar radiation is trapped in the soil using plastic mulch film. may be used to heat up the soil and destroy weed seed using plastic mulch film.

Other above-ground thermal weed control approaches include flame weeding and steam weeding. These are designed to expose weeds to 'sufficient heat to disrupt cell membranes, destroying leaf and meristematic tissues' (Henderson & Bishop, 2000). Various unshielded, shielded, and surface options are available to manage weeds above-ground. These tend to be most effective in managing recently germinated weeds.

Sub-surface steaming can also be used to heat and destroy weed seed beneath the soil surface, as well as control some soil-borne diseases.

These thermal weed control methods are most likely to be relevant to low-till and permanent bed cropping systems, and to organic vegetable farms where herbicides are not available to the grower.

Interest in controlling weeds using microwave energy has been growing in recent years due to increasing concerns about herbicide resistance and chemical residues in the environment. Microwave weed control is still under development, but in time it may offer an alternative to other non-chemical weed control methods including tillage and hand weeding, as well as the other thermal treatment techniques discussed here.

Soil solarisation

Soil solarisation offers an alternative to chemical fumigation (see 'Chemical fumigation') in managing soil-borne pests as well as weed seed and seedlings before the vegetable crop is sown or transplanted.

It involves using clear plastic mulch film to trap solar radiation in moist soil for several weeks. By increasing temperature in the upper layers of the soil, solarisation can reduce the number of viable weed seed within the top layer of soil, and killing any germinating plants.

Advantages

- Effective in managing annual broadleaf weeds common to vegetable production.
- Applicable in specific circumstances, e.g. strategic application to dense, smaller infestations, or in smaller-scale organic production.
- Even where weed seed is not destroyed by solarisation, weeds may still germinate and then die beneath the plastic film.
- Crop yields may be higher in solarised soils due to reductions in soil-borne disease.
- Clear mulch films may be effective in managing nutgrass (*Cyperus rotundus*) tuber production.
- High soil temperature required suggests its benefits may be greatest in northern vegetable production regions.

Disadvantages

- Relatively expensive to purchase, apply and dispose of the mulch film
- Potentially requires up to 60 days out of production.
- Disposal of clear plastic mulch films has the same waste management problems as conventional plastic mulch disposal (see 'Plastic mulch films').
- Less likely to work in southern cool-climate vegetable production regions due to the high soil temperatures required.
- Requires well-formed smooth beds and high soil moisture at time of application for greatest success.
- Wheel tracks not subjected to the plastic film still need to be managed for weeds.
- Biodegradable mulch films (see 'Biodegradable mulch films') are not suited to soil solarisation.

Timing

Most likely to be applicable during summer fallows (high soil temperature and no growing crop).

May be applicable if crops are grown using a plastic mulch film, however the clear film preferable for soil solarisation may not be practical to use with a vegetable crop.

How to use

Soil solarisation is most effective when the plastic mulch is laid on a well-prepared, smooth and recently irrigated paddock.

Plastic film should be left in place for between 30 and 60 days. The time required depends on species present within the seed bank, with time and temperatures required to destroy seed and seedlings varying amongst species.

The plastic film will then need to be removed before preparation for the next cash crop. Solarised soils can be planted out with a cash or cover crop if desired, immediately after treatment. If tillage is needed before the crop is planted, a shallow cultivation post-solarisation and prior to planting (less than 5 cm) will help avoid bringing viable weed seed to the surface.

If you grow crops using a plastic mulch production system (e.g. cucurbits), the clear solarisation film may also potentially be left in place and used for the next crop which may be transplanted through the plastic film. This step will require careful consideration however, as the clear film may still heat the soil to a temperature unsuited for growing a successful crop. In this case, clear film may need to be removed and replaced with your usual black or white film.

Maximising success

- **Smooth bed surfaces** allow the plastic film to adhere more closely to the soil surface and minimises the risk of the plastic being punctured.
- **Wet soil** conducts heat more effectively than dry soil, and ideally will be saturated to at least 70 per cent of capacity at the time the plastic is applied to maximise effectiveness.
- **Relatively thin clear plastic film** has been found to be more effective in solarising the soil than black or white mulch films commonly used in some vegetable crops. Thin clear films heat the soil to a higher temperature, which is more effective in reducing weed seed viability and controlling recently germinated seedlings.
- Soil solarisation is **most effective during the hottest months of the year** and in hotter climates. Soil temperatures may reach up to 70°C in warmer vegetable growing zones.

Integration with other techniques

Techniques to *immediately precede* soil solarisation will focus on effective management of weeds within the previous cash crop, such as **post-emergence and post-plant herbicides**, **inter-row tillage**, and **hand weeding** with a focus on minimising weed seed production in the crop. They may also include **fallow and postharvest herbicides** (if registered for the crop). Immediately before the film is applied for solarisation, **tillage** will be required to form smooth, weed-free beds.

Non-selective herbicide may need to be applied to wheel tracks not covered by the solarising film layer to ensure weeds do not produce seed that will become an issue in the subsequent cash crop.

Once the plastic film is removed, **non-selective herbicide** and/or **tillage** may be needed *immediately following* soil solarisation, to control any weeds that have germinated beneath the film layer, but not been killed by the solarisation effect.

Integration with other techniques will depend on farm circumstances (crops, soil and climate, staff, budget, and timing within crop cycle).

Key references and further reading

Candido, V., D'Addabbo, T., Miccolis, V., Castronuovo, D. 2011. Weed control and yield response of soil solarization with different plastic films in lettuce. Scientia Horticulturae 130: 491-497.

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Thermal (flame and steam) weeding

Flame weeding ('flaming') involves using natural gas- or propane-fuelled burners to expose weeds to sufficient heat to control weeds. Where used within vegetable crops, it is a pre-plant or early post-plant replacement for knock-down and/or selective herbicides.

Flaming implements tend to be hand operated, either wheeled or hand-held with the fuel supply (generally a propane gas bottle) mounted on a backpack or trolley.

Hooded flaming implements are also available, distributing heat more efficiently and directly onto plant surfaces, and reducing fuel usage.

Soil steaming ('steaming') has the potential to be very effective for control of weeds in vegetable crops. As with soil solarisation, steaming has a number of benefits for soil and crop health other than for weed management, by allowing some control of bacteria, viruses, fungi, and nematodes that can harm the crop.

There are a range of steaming options available, including:

- **surface-level steaming** wands, connected to a steam generator, to kill surface-level plants (hooded and non-hooded options are available); and
- **soil thermal weeding** which involves injecting steam into the top layer of sheeted/covered soil to destroy weed seed beneath the surface.

Surface-level steaming and soil thermal weeding is usually carried out before crops are planted, due to the size of the equipment and likely damage to a growing crop.

Advantages

- Their relative portability means that hooded flaming implements could be used after the crop has been transplanted, though care and precision is required to ensure that crop plants are not damaged.
- Flaming and steaming provide an alternative to commonly-used pre-plant and potentially early post-plant knock-down herbicides. They leave no chemical residue, and leave the soil undisturbed, assisting with reduced tillage.
- Flaming and steaming are particularly relevant to organic vegetable production.
- Flaming has some potential to destroy viable seed and reduce weed germination, but will be most effective when seed is near the soil surface.
- Flaming and steaming are most successful in managing recently germinated broadleaf weeds. Kristiansen and Smithson (2008) found that this approach reduced broadleaf weeds by around 50% to 60%.
- Surface-level steam weeding has advantages over flaming, including better heat transfer and reduced fire hazard risk.
- Soil thermal weeding can reportedly kill a broad spectrum of weed seed within the top layer of soil from which weeds usually germinate.

Disadvantages

- Flaming will be less effective in windy conditions, and poses a potential fire risk of conditions are also dry. It will not be allowable where fire restrictions are in place.
- Flaming and surface-level steaming can be relatively ineffective in controlling grass weeds, which have a growing point either concealed or beneath the soil surface – meaning they are well placed to recover after treatment. Some success may be achieved against very recently germinated grass weeds.
- Flaming and surface-level steaming are relatively ineffective in managing larger weeds.
- Set-up costs (flaming, steam or soil thermal weeding equipment) are high, but this may be acceptable for organic farmers in particular if their use significantly reduces tillage and hand weeding costs.
- All thermal weeding using flame and steam requires relatively large amounts of fossil fuel.
- Steam and soil thermal weeding requires large quantities of water.
- Flame, steam and soil thermal weeding impose slow work rates (equating to relatively high labour costs).

Timing

Flaming, surface-level steam weeding and soil thermal weeding are designed to be used in crop fallow periods, within recently tilled clean beds that have been prepared for the next crop.

However, surface-level steam weeding with hooded equipment may be used to manage weeds within crops.

How it works

Flaming and surface-level steaming expose plant parts to sufficient heat to damage plant parts, disrupt growth processes and result in weed death.

Soil thermal weeding works by heating up the weed seed buried in the soil to a lethal temperature using sheet-steaming equipment. It is typically carried out within the top 5 cm of soil, before the crop is planted.

Maximising success

- Effectiveness is maximised if flaming or surface-level steam weeding is carried out regularly (for example weekly application for three weeks).
- Apply to **smaller weeds**, which are more susceptible to flaming and steaming than larger, established weeds. These weeds may be stimulated by irrigation or recent rainfall.
- **Slow application speeds** may be necessary for flaming and surface-level steaming, to ensure heat is being transferred to the soil surface for sufficient time to kill any weeds present.
- Providing the soil is not tilled again prior to the crop being planted, the results of a soil thermal treatment (in destroying many viable weed seed) are likely to last for the life of the crop.
- Soil thermal weeding equipment that uses hot air rather than steam to heat the soil was under development at the time of writing, with potential advantages including lower cost, greater simplicity, and significantly reduced fuel use.

Integration with other techniques

Non-selective herbicide use and **tillage** may *immediately precede* flaming and surface-level steaming, to control all weeds present in the recently harvested crop and to establish a clean bed in which these activities can be carried out.

False seed beds may be used *alongside* flaming and surface-level steaming; recently germinated weeds may be controlled using these surface-level thermal approaches within the false seed bed, in place of shallow tillage or non-selective herbicides.

Techniques to *immediately follow* pre-plant flaming, surface-level steaming and soil thermal weeding will involve the range of approaches used to manage weeds immediately before and within a crop: for example **pre-emergent herbicide**, **selective herbicide**, **inter-row tillage**, and **hand weeding**.

Integration with other techniques will depend on farm circumstances (crops, soil and climate, staff, budget, and timing within crop cycle).

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Microwave weeding

Microwave heating for controlling weeds is no different to a standard microwave oven found in most kitchens; the technology heats up weed plants or weed seeds using indirect heating, and essentially cooks them. Microwave treatment of weeds and weed seed works by heating the water contained in the plant cells. This creates a series of steam explosions which rupture the cell walls of plants and destroy these as well as weed seed.

Recent improvements in microwave weed control technology suggests that the energy required is comparable to or better than surface-level steaming, soil thermal weeding and flame weeding in killing weeds and weed seeds buried in the soil.

This technology was not available commercially in Australia at the time of writing. However, an Australian company, Growave, was conducting trials to prove the concept and commercialise microwave weeding equipment.

Possible advantages

- Dual management of weeds as well as reduction of the soil weed seed bank.
- Reduced reliance on herbicides and an option for control of herbicide-resistant weed populations - reported to be effective in controlling all weed species.
- May help vegetable growers to reduce the number of tillage passes required to manage weeds.
- Will not leave any residues in the soil.

Possible disadvantages

- As with all thermal approaches, likely to be energy intensive.
- Slow operating speeds.
- Potential harm to beneficial soil biota.

Timing and usage

- For soil treatment to reduce the weed seed bank, microwave may be used at any time during the fallow.
- To control growing weeds, microwave weed control may be used pre-plant but also as an inter-row option if the machinery is set up appropriately.
- Microwave weed control may prove useful if used as part of a **false seed bed** to manage weeds as well as reduce the weed seed bank shortly before the crop is sown or planted.

Part 3H: Automation and guidance technology

Various technologies are becoming available, or more affordable, that will have a growing impact on how weeds are managed on vegetable farms in the near future - in addition to transforming management of the whole farming system.

GPS guidance technology is now commonly available to vegetable growers to allow a permanent or semi-permanent bed system to be established on the farm, introducing the possibility of precision reduced tillage to vegetable production.

Strip tillage is an increasingly popular form of reduced tillage being introduced on Australian vegetable farms, though its implications for weed management were not quantified at the time of writing.

Automated or robotic weeding systems, using advanced sensing equipment to differentiate weeds from crop plants and control them within the crop beds either by shallow intra-row tillage, direct herbicide application, or chipping, have been under development for over a decade. The push for robotic weeding has been driven by relative lack of herbicides registered for the vegetable industry; the increasing cost of hand weeding; and lack of reliable labour supply

Robotic weeding technology is gradually becoming more affordable and effective. Australian researchers have predicted that in the next few years robotic weeding will become economically viable for use in vegetable production, starting with larger-scale commercial farms. It has the potential to allow growers to reduce or negate entirely the cost of hand weeding, some tillage operations, and significantly reduce overall herbicide use by allowing targeted application.

Controlled traffic farming and reduced tillage

Controlled traffic farming (CTF) involves establishing permanent wheel tracks as well as permanent or semi-permanent (e.g. seasonal) crop rows, using Global Positioning Systems and related guidance technology.

CTF also makes it possible to implement a **reduced tillage** system, allowing a lower rate of soil compaction than in conventional horticulture. This approach is becoming more feasible in vegetable production due to the availability of no-till planters such as seed drills for certain crops.

Advantages

- Reduced weed seed stimulation through tillage, and therefore potentially less weed competition in the beds.
- More efficient use of farm resources and equipment, including potential for reducing the amount of herbicides used.

Disadvantages

- High up-front cost in satellite guidance systems, paddock layout design changes and potentially investment in equipment to allow CTF and reduced tillage.
- Greater reliance on herbicides in fallow periods can increase the risk of herbicide resistance (see 'Herbicide resistance').
- Reduced and especially zero tillage may change the weed spectrum on the farm – research suggests this approach favours winter annuals, biennial and even perennial weed species.

How to use

Seasonal or permanent crop beds, where the primary goal is to enhance soil structure and health, may mean relying increasingly on **non-selective herbicides** to manage weeds and crop residues in order to carry out less tillage passes during an annual crop cycle.

CTF and semi-permanent or permanent beds can also be integrated with **cover crop mulches** (see 'Cover crop mulches') and strategic use of **pre- and post-emergent herbicides** (see 'Pre-plant/pre-emergent residual herbicides' and 'Post-emergence and post-plant selective herbicides') to control weeds in the early crop stages. Used in this way, it offers a potential alternative to plastic mulch and drip irrigation systems used in producing high-value crops such as cucurbits.

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Information is also available via the Australian Controlled Traffic Farming Association: https://www.actfa.net/.

Strip tillage

Strip tillage combines no till and standard tillage to allow row crops to be produced. Only the planting rows are disturbed in strip tillage, commonly by vertical implements not horizontal or shallow-angled implements.

Outside the planting rows the ground remains untilled, thus retaining surface residues, preserving soil moisture, maintaining soil structure, and reducing the risk of erosion. The untilled area can be used to grow green manure or cover crops (see 'Part 3E: Green manure and biofumigant cover crops').

Adoption of this approach is increasing amongst Australian vegetable growers. Because this is a relatively new approach, weed management 'advantages' aren't really quantified yet.

Advantages

- When used as an alternative to bare crop beds, strip tillage appears to produce comparable crop yields.
- Fuel conservation is likely due to partial tillage of the crop bed.
- Reduced soil erosion can result from partial ground cover retention.
- Strip tillage maintains higher soil organic matter levels, quality and fertility, soil moisture and soil biota than conventional tillage.
- Lower crop management costs due to reduced number of tillage operations needed.

Disadvantages

- Where strip tillage has been shown to result in reduced yield compared to conventional systems, it is often associated with increases in weed populations.
- When used as an alternative to **plastic mulch beds**, research suggests that strip tillage produces lower yielding crops.
- Strip tillage, as well as planting in this system, is likely to be more complex than conventional tillage and planting/sowing, requiring specialised strip tillage implements and highly accurate GPS guidance.
- The raised strip tillage residue takes up to several months to flatten down before planting or sowing is possible.
- Best suited to row crops with wider spacing, due to bed residue maintenance needs.
- As with reduced tillage, strip tillage can increase the risk of herbicide resistance developing, due to increased reliance on non-selective herbicides in particular.

Timing

The mulch layer will be established and managed in much the same way as a killed cover crop mulch (see 'Cover crop mulches').

Following cover crop mulch termination, the strip till operation may produce ridged soil residues which it may not be possible to plant or sow the crop in to immediately.

These factors mean that considerably more time may be required in the rotation to prepare the beds using strip till techniques. Therefore this approach is less likely to be suited to vegetable production systems where short fallow periods are common.

How to use

A cover crop mulch is the starting point of a strip tillage system. The cover crop may be controlled prior to strip tillage using a variety of options including mowing or slashing, non-selective herbicide application, or crimper rolling, to ensure the cover crop does not out-compete the cash crop.

Within the resulting killed cover crop mulch, narrow parallel strips of between 150mm and 300mm in width (and anywhere between 50mm and 350 mm in depth) are tilled using specialised equipment. Crops are planted or sown within these parallel strips.

Weed management implications

The implications for weeds in the tilled and non-tilled strips do not appear to be understood yet.

Weed seed within the mulched strips that may otherwise be buried using a conventional tillage pass remain on the surface in a strip tillage system. If the mulch layer is thin, this can potentially result in weed cohorts emerging early in the crop growing season. On the other hand, because there is no tillage within these strips, viable weed seed will not be brought to the surface. Over time, then, fewer surface weeds may be expected to emerge in a strip tillage system compared to conventional tillage.

Non-selective herbicide will often be the 'go-to' option for weed management in strip tillage. Be aware of the potential for herbicide resistance to become a more significant problem, and manage weed populations effectively where resistance is suspected (see 'Herbicide resistance').

Integration with other techniques

Weed management in a strip tillage system will incorporate several techniques:

- Suppression of weed growth before the strip tillage is carried out through **non-selective herbicide** application to bare fallow beds; growth of **cover crop** within which the strip tillage system will be established; and conversion of this crop into a **killed cover crop mulch** layer. Ideally, the cover crop layer will be thick enough to provide good suppression of weeds once converted into a killed mulch.
- **Non-selective herbicide** may be used again, not only to kill the cover crop mulch, but also to manage recently germinated weeds after the tilled strips have been established, and before the crop is either planted or sown. This is similar in principle to **stale and false seed beds**.
- Where available, **selective herbicides** may be used within the strip till crop to manage particular weed species.
- Growers may also carry out selective hand weeding, or spot-spraying using non-selective herbicide to manage large weeds within the growing or mature crop.

Following harvest, effective management of weeds in the crop residue and killed mulch, and cleaning up the beds as soon as possible, will help keep the weed seed bank down, and contribute to the competitiveness of the next cash crop this is likely to involve additional **non-selective herbicide application**, and **tillage**.

Integration with other techniques will depend on farm circumstances (crops, soil and climate, staff, budget, and timing within crop cycle).

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Robotic weeding

Automated weeding using advanced sensing and application equipment has been under development for over a decade. Technology is being developed to differentiate weeds from crop plants, or weeds from bare ground. Control options using robotics include shallow inter and/or intra-row tillage, targeted or direct herbicide applications.

A push for robotics weeding technology has been driven by the evolution of the technology itself, relative lack of herbicides registered for the vegetable industry (particularly within an actively growing crop) and increasing hand weeding costs. Robotic weeding technology is gradually becoming more affordable and effective, and is close to commercial implementation at the time of writing.

Australian researchers and agribusiness operators have predicted that robotic weeding will become economically viable for use in vegetable production in the next few years, starting with larger-scale commercial farms. A robotic weeder can potentially allow growers to reduce or avoid entirely the cost of hand weeding, some tillage operations, as well as herbicide application using a tractor-mounted spray rig.

Figure 3-43. This field robotics device, developed by the University of Sydney and Agerris, is designed to carry out non-chemical weeding and intelligent spraying through weed detection sensors (Location: Richmond, New South Wales).

Potential advantages

- Providing an alternative to expensive weed management tactics such as hand weeding and tillage.
- Reduced herbicide costs through targeted rather than broad-scale herbicide application.
- Herbicides can be used in a targeted fashion at full rates to maximise the chance of successful weed management, rather than more cost-effective lower rates on a broad-scale.
- Being able to work continuously (or until battery re-charge).
- Being able to operate autonomously and systematically, without need for human intervention.
- Being able to operate collectively – several robotic weeders have the potential to work together.
- Given relative lightness compared to a tractor with spray rig, they have the potential to get onto the paddock sooner after rainfall, managing weeds before they become larger and more problematic. This can also be of benefit by reducing soil compaction.
- Eventually, robotic weeders may be able to classify each weed based on its size and/or species, and determine whether herbicide, mechanical weeding, or thermal weeding is most likely to achieve success – and to act accordingly from amongst these options.
- Helping to address the issue of herbicide resistance in several ways:
  - By allowing for targeted mechanical control of herbicide-resistant weed species relatively early in their life cycle.
  - Through the robotic unit carrying several herbicide options, and choosing which to apply to each weed species. These selections may be based on a pre-programmed strategy which takes herbicide resistance management into account.
  - Via robotic weeding units that undertake targeted control of weeds through soil disturbance rather than herbicide application – for example, shallow tillage or targeted tillage.
- Significantly reducing the impact of herbicide application on the environment, through a shift from broad-scale to targeted application, and significant reductions in amount of herbicide used.
- Having a number of other possible uses, such as fertiliser application and yield estimation.

Timing

Some robotic weeders are designed to use within actively growing crops, and will be most relevant when the crop plants are relatively small and can be differentiated easily from weeds.

Other systems are capable of distinguishing between plants and bare ground, such as the WEED-IT precision sprayer available in Australia. These may be used during crop fallow periods to target weeds for herbicide application to reduce the quantity of herbicide used; or within young vegetable crops between the crop lines and in the wheel tracks, providing a shrouded boom is used to reduce the risk of herbicide drift.

How it works

Starting with relatively simple systems which required knowledge around the exact placement of crop plants using GPS technology, researchers have progressed to more advanced robotic weeding systems which use optical sensors to differentiate crop plants from weeds (or weeds from bare ground) and implement control of the weeds through precision tillage, spot-spray or touch herbicide application, or potentially other methods under development such as microwave technology.

This publication should be cited as: Kristiansen, P., Coleman, M., Sindel, B., and Fyfe, C. 2021. Integrated weed management for the Australian vegetable industry. Part 3: Methods of integrated weed management in vegetable production. University of New England, Armidale.

v 1.0; May 2021.

Hort Innovation Strategic levy investment | VEGETABLE FUND

This project has been funded by Hort Innovation using the vegetable research and development levy and funds from the Australian Government. For more information on the fund and strategic levy investment visit horticulture.com.au

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