INTEGRATED WEED MANAGEMENT

GRDC™
GRAINS RESEARCH & DEVELOPMENT CORPORATION

NSW GOVERNMENT | Department of Primary Industries

NSW GOVERNMENT | Local Land Services

WORKSHOP HANDBOOK

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This handbook was devised to summarise key aspects of the third edition of that manual and to support the delivery of integrated weed management workshops across the GRDC Northern region. These workshops aim to increase grower and advisor understanding of integrated weed management control strategies and how they can be implemented to reduce targeted weed numbers.

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SECTION 1: WORKSHOP OBJECTIVES

OVERVIEW

Weeds continue developing resistance, moving and adapting to new areas and changes in our production systems. A 2016 study found that weeds cost the Grains Research and Development Corporation (GRDC) Northern Region grains production an estimated $141 million dollars or $35 per hectare annually (Llewellyn et al. 2016). While the impact varies paddock to paddock it is important to actively manage weed numbers to prevent land from becoming unproductive. Therefore, it is important that grain growers and advisors review and employ an integrated approach to weed management principles to try and stay one step ahead. To help manage these weed issues GRDC, in conjunction with NSW Department of Primary Industries (NSW DPI) and NSW Local Land Services (NSW LLS), have established a series of workshops to:

- Establish grower and advisor understanding of weed management issues; and
- Increase grower and adviser understanding of integrated weed management control strategies and how they can be implemented to reduce targeted weed numbers.

SECTION 2: EVALUATION

ACTIVITY

Assess your weeds, how do you control of them now, how do you plan on controlling them in the future?

1. What are my weeds of concern?

2. How do I monitor them?

3. How do I control them (now)?

4. Is it working? For how long?

5. What's the next step? How do I plan on getting/staying ahead of the weeds?

6. What do I want to do? Spray more, use technology, new methods?

7. What would I like to know more about?

SECTION 3: INTEGRATED WEED MANAGEMENT

WHAT IS INTEGRATED WEED MANAGEMENT?

In 2016 the total cost of weeds to Australian grain growers was estimated to be $3.3 billion per annum. Overall, this equates a reduction to crop yields of about $33/ha, with growers spending $113/ha on weed control. This high cost of management is in part due to herbicide resistance, the cost of additional herbicides, and the use of other control tools to manage these weeds. Herbicide resistance has continued to become more widespread, reducing or eliminating the effectiveness of some herbicide mode of action (MOA). This coupled with the dwindling development of new herbicide chemistries or MOA to replace ineffective herbicides means that concerted efforts are needed to maintain effective control of weeds whilst preserving the longevity of herbicides. The loss of these herbicides is of particular concern to farmers, particularly glyphosate. A 2016 study found that herbicide resistance affects 43% of cropping land on average, with 64% of growers identifying some herbicide resistance on their farm. To date, 49 weed species in Australia have confirmed resistance to herbicides, 17 of which are resistant to glyphosate. This is an increase from the six species with glyphosate resistance as reported in 2013.

Integrated weed management (IWM) is a system for managing weeds over the long term, particularly the management and minimisation of herbicide resistance. There is a need to combine herbicide and non-herbicide methods into an integrated control program. Given that there are additional costs associated with implementing IWM, the main issues for growers are whether it is cost-effective to adopt the system and whether the benefits are likely to be long-term or short-term in nature.

SECTION 4: IWM ASSESSMENT – IS IT WORTH DOING?

IS INTEGRATED WEED MANAGEMENT (IWM) COST-EFFECTIVE?

IWM is definitely cost-effective in the longer term. In the short term, many farms don't adopt IWM because of the added costs and perceived complexity; however, research and farmer experience have shown that failure to adopt IWM leads to herbicide resistance.

In a 2004 survey of Western Australian grain growers it was realised that the adoption of IWM practices was associated with the herbicide resistance status of a farm. Although farms without resistance also used IWM, practices were more likely to be used when herbicide resistance was present. For example, IWM tactics such as the use of crop-topping was three times greater on farms with resistance than on those without. On average, farms with herbicide resistance used a greater number of weed control practices (nine) than farms without herbicide resistance (six). For most Australian farming systems, the adoption of IWM is often an outcome of the identification of herbicide resistance.

There are four key factors that influence the adoption (or non-adoption) of IWM:

1. Expectation of new herbicide technology

Herbicides are regarded as having greater weed control efficacy than non-herbicide controls. While current herbicides remain effective there is reduced incentive to adopt alternative control options. The development of herbicide resistance indicates a reduction in the future effectiveness of herbicide options, and should increase the attractiveness of IWM. A 2016 study found that the majority of growers agreed that new selective and non-selective herbicides will be available within the next 10 years to control current resistant weeds, which may reduce the incentive to adopt IWM. At time of publishing, several new herbicides are in development and are undergoing registration. New modes of action offer the opportunity to delay resistance to any one herbicide; however they do not prevent the eventual development of resistance. Current and any future herbicides need to be used in an integrated weed control strategy to best preserve their effectiveness and maintain superior control of weeds.

2. Regression and mobility of resistance

The 2002 study surveyed growers' perceptions of whether herbicide resistance will disappear of its own accord (when herbicides are no longer used and the less fit of the resistant plants fail to maintain their proportion in the population) and how easily herbicide resistance will spread (via means such as pollen flow, seed movement and contaminated seed and fodder).

The survey found that:

- Up to 46% of growers thought that resistance would disappear of its own accord.
- Nearly 14% thought self-disappearance to be highly likely.
- 54% of growers thought importation of resistance after 10 years was likely.
- 21% believed importation to be highly likely.

A 2006 study found similar trends in a study of farmers and agronomists in northern New South Wales and Queensland, where 30% of respondents thought herbicide resistance only lasted up to five years while a further 10% did not know.

A 2016 study of growers across Australia found mixed perceptions on the likelihood of gaining glyphosate resistance in one of their paddocks through grain or pollen movement 42% to 39%.

3. Efficacy of alternative IWM options

In the absence of herbicide resistance, post-emergent selective herbicides are perceived by growers as having the highest reliability and efficacy among available IWM options. In contrast, some ‘traditional’ control methods such as stubble burning and cultivation are regarded as having much lower efficacy and large variances. Although it is recognised that each control tactic has its own impact on weed mortality and/or seed set, an increasing number of growers realise that very effective weed control can only be achieved with a targeted combination of a wide range of strategies. As control tactics are imposed at different times, their combined impacts are multiplicative rather than additive. For example, the combined effect of two control tactics each with 40% survival is 16% survival.

4. Attitudes to short-term profit versus long-term returns

IWM is widely regarded as providing a long-term approach to weed management, in which there are likely to be initial upfront costs to achieve longer-term gains from reduced weed populations. In some circumstances growers may make suboptimal weed management decisions due to their specific planning objectives. For example, where there are short-term financial pressures (e.g. debt servicing requirements) growers may make decisions that increase current period profits but that may have negative long-term consequences (e.g. herbicide resistance).

Returns of an individual enterprise in the short term are usually measured through a gross margin budget, which is determined by factors such as crop yield, price, the costs of both herbicide and non-herbicide weed control, and other inputs such as seed and fertiliser. Crop yield is directly influenced by weed density, which itself is a function of weed control. For short-term decision making the goal of the grower managing a weed problem is to determine the optimal level of herbicide and non-herbicide inputs for a given weed density that will maximise the crop gross margin.

However, this approach to measuring returns from weed management ignores a critically important economic factor, namely the carryover of the weed seedbank and its impact on returns in future years.

A weed control decision not only has an impact on returns for the current crop, but also affects yields in later years (for good or bad) due to its impact on the weed soil seedbank. Calculating returns over the longer term such as a period of 20 years is a better approach for determining the value of the economic benefits of IWM.

A longer-term approach is also able to account for important economic factors such as changes to weed seedbanks from one year to the next due to weed management actions and the impact of herbicide resistance. The role of good agronomic practices such as more competitive crops, alternative crops in a rotation and pasture phases should be valued along with weed management tactics.

The longer-term view of weed management can be assisted by adopting the concept of Tactic Groups. This approach coordinates weed control practices with the life cycle of weeds, and emphasises the need to avoid any practices which may add viable weed seeds to the seedbank.

SECTION 5: THE IWM TOOLBOX – AGRONOMY AND TACTICS

Changes in agronomy and the introduction of new or additional weed management tactics can work together to provide strong and lasting weed control. This section provides a summary of Agronomy and Tactics to assist growers in understanding the principles of each method.

AGRONOMY – TAKING CONTROL OF WEED MANAGEMENT

Significant or subtle changes in agronomy can enhance the impact of weed management tactics. Increases in sowing rate, reduction in row spacing, adjustments to fertiliser application rate and changes in crop variety choice can significantly improve crop competition, which in turn improves weed control results. More substantial changes, such as choosing a different crop type, can enable the inclusion of additional tactics and expand the opportunities for highly effective weed control.

1. Crop choice and sequence

Many agronomic management implications arise from the sequence in which crops are sown. These implications include benefits that can enhance weed management. Planning crop rotation in advance minimises disease and insect problems and maximises crop fertility. With disease, insects and fertility managed optimally, crops become more competitive against weeds.

The implementation and/or effectiveness of some weed management tactics rely on specific crop type and variety, or the sequence of cropping. For example, tactics that aim to kill weeds (often with a herbicide) can be greatly enhanced by growing a more competitive crop type or variety.

At the same time the ability to control a target weed in a specific crop may be so limited that it is best to avoid growing that particular crop in paddocks where the target weed is a problem. For example, winter pulses should not be grown in paddocks where black bindweed (*Fallopia convolvulus*) or wireweed (*Polygonum* spp.) are a problem, and sunflowers should not be grown in paddocks with heavy broadleaf weed burdens.

Crop and variety choice is also important when implementing weed management tactics that relate to controlling in-crop seedset. These tactics are much less detrimental to crop yield and quality where the crop variety matures before the weed species.

Table 1 provides key information about winter crop types to assist in making crop choices. Knowledge of relative competitiveness, sowing time, maturity, available herbicide options and difficult to control ('No Go') weeds is important. Similar information about specific varieties should be sought on a local basis.

Weed competitiveness varies between crop types and between varieties within a crop type. Growing a competitive crop in paddocks with high weed pressure will enhance the reduction in weed seedset obtained through employing weed management tactics. It will also reduce the impact that surviving weeds have on crop yield.

Sowing bread wheat or barley is recommended to maximise crop competition (Storrie et al 1998). For example, in areas where summer crops can be grown successfully, a winter fallow–summer sorghum rotation before wheat is a very effective way of managing wild oats (*Avena* spp.) and paradoxa grass (*Phalaris paradoxa*).

Key benefit

- Crops with dense canopies act as more effective break crops.

Key practicalities

- Selecting crop sequences and varieties to deal with the significant pathogens and nematodes of the paddock in question is good management.
- Weeds are alternate hosts to some pathogens. Effective integrated weed management during the fallow and in-crop can reduce disease pressure.
- Rhizoctonia can affect seedling crop growth, leaving the crop at greater threat from weed competition.
- Weeds can increase moisture stress within a wheat crop, exacerbating yield loss from crown rot.

Table 1 Crop choice options to aid weed management.

Crop	Competitive ability	Relative sowing time	Relative maturity	Available herbicide options	'NO GO' weeds †	Key weeds to target	Most suitable tactics other than pre- and post-emergent herbicide application	Agronomy to enhance weed management ‡
Barley	High	Mid–late	Early	▪ Grass – several ▪ Broadleaf – many	▪ Barley grass ▪ *Vulpia* spp. ▪ Brome grass	▪ Most broadleaf	▪ Autumn tickle ▪ Double knockdown ▪ Delayed sowing ▪ Crop desiccation ▪ Winter clean pasture in previous year	▪ Variety choice ▪ Improved fertiliser placement ▪ Increased sowing rate ▪ Good seed (clean and high germination rate) ▪ Direct drill
Canola – imidazolinone tolerant (IT) varieties	Medium	Early	Early	▪ Grass – many ▪ Broadleaf – several	▪ Group B resistant brassica weeds (e.g. wild radish, wild mustards, wild turnip)	▪ Grass weeds – particularly brome grass ▪ Groups A and M resistant grass weeds ▪ 'Imi' susceptible broadleaf weeds	▪ Autumn tickle ▪ Burn residues (not sandy soils) ▪ Crop desiccation ▪ Windrowing ▪ Seed catching ▪ Windrow/burn residues ▪ Winter clean pasture in previous year	▪ Variety choice ▪ Improved fertiliser placement ▪ Direct drill
Canola – standard varieties	Medium	Early	Early	▪ Grass – several ▪ Broadleaf – limited	▪ Group A resistant grasses ▪ Brassica weeds (e.g. wild radish, wild mustards, wild turnip) ▪ Fumitory ▪ Black bindweed ▪ Vetch	▪ Grass weeds	▪ Autumn tickle ▪ Burn residues (not sandy soils) ▪ Crop desiccation ▪ Windrowing ▪ Seed catching ▪ Windrow/burn residues ▪ Winter clean grasses in previous year	▪ Variety choice ▪ Improved fertiliser placement ▪ Direct drill
Canola – glyphosate tolerant (RR) varieties	Medium	Early	Early	▪ Grass – many ▪ Broadleaf – several	▪ Glyphosate resistant weeds ▪ Brassica weeds	▪ Grass weeds ▪ Some broadleaf weeds	▪ Autumn tickle ▪ Burn residues (not sandy soils) ▪ Crop desiccation ▪ Windrowing ▪ Seed catching ▪ Windrow/burn residues	▪ Variety choice ▪ Improved fertiliser placement ▪ Direct drill

† Presence of listed weeds severely limits use of crop type in a sustainable cropping system.

‡ Highly suited tactics that can be used in addition to the traditional pre-sowing non-selective knockdown, pre-emergent residual herbicides and early post-emergent herbicides.

Crop	Competitive ability	Relative sowing time	Relative maturity	Available herbicide options	'NO GO' weeds †	Key weeds to target	Most suitable tactics other than pre- and post-emergent herbicide application	Agronomy to enhance weed management ‡
Canola – triazine tolerant (TT) varieties	Medium	Early	Early	▪ Grass – many ▪ Broadleaf – several	▪ Triazine resistant brassica weeds	▪ Grass weeds ▪ Triazine susceptible broadleaf weeds ▪ Fumitory	▪ Autumn tickle ▪ Burn residues (not sandy soils) ▪ Crop desiccation ▪ Windrowing ▪ Seed catching ▪ Windrow/burn residues ▪ Winter clean grasses in previous year	▪ Variety choice ▪ Improved fertiliser placement ▪ Direct drill
Chickpeas	Poor	Mid–late	Late	▪ Grass – several ▪ Broadleaf – limited	▪ Fumitory ▪ Black bindweed ▪ Wireweed (no-till and stubble retention) ▪ Vetch	▪ Grass weeds such as Feathertop Rhodes grass	▪ Double knockdown ▪ Wide row – shielded spraying or inter-row cultivation and band spraying ▪ Crop-topping ▪ Desiccation ▪ Wick/blanket-wiping	▪ Improved fertiliser placement ▪ High sowing rate
Faba beans	Medium	Mid	Mid–early	▪ Grass – several ▪ Broadleaf – limited	▪ Wild radish ▪ Musk weed ▪ Vetch	▪ Grasses	▪ Crop-topping ▪ Windrowing ▪ Windrow/burn residues	▪ Improved fertiliser placement ▪ High sowing rate
Field peas	Medium	Late	Early	▪ Grass – several ▪ Broadleaf – several	▪ Fumitory ▪ Bifora ▪ Vetch	▪ Grasses	▪ Delayed sowing ▪ Double knockdown ▪ Crop-topping ▪ Desiccation ▪ Green/brown manuring	▪ Variety choice ▪ Improved fertiliser placement
Lentils	Poor	Late	Early	▪ Grass – several ▪ Broadleaf – limited	▪ Brassica weeds ▪ Vetch	▪ None	▪ Wick/blanket-wiping ▪ Crop-topping	▪ Improved fertiliser placement
Lupins – narrow-leafed and *L. albus*	Poor	Early	Late	▪ Grass – several ▪ Broadleaf – many	▪ Sand plain (blue) lupin	▪ *Vulpia* spp.	▪ Residual herbicides ▪ Windrowing ▪ Crop-topping ▪ Desiccation	▪ Improved fertiliser placement ▪ High sowing rate

† Presence of listed weeds severely limits use of crop type in a sustainable cropping system.

‡ Highly suited tactics that can be used in addition to the traditional pre-sowing non-selective knockdown, pre-emergent residual herbicides and early post-emergent herbicides.

Crop	Competitive ability	Relative sowing time	Relative maturity	Available herbicide options	'NO GO' weeds [†]	Key weeds to target	Most suitable tactics other than pre- and post-emergent herbicide application	Agronomy to enhance weed management [‡]
Oats – graze and grain	High	Early–mid	Early–mid	▪ Grass – limited ▪ Broadleaf – many	▪ Wild oat ▪ Brome grass ▪ Barley grass ▪ *Vulpia* spp.	▪ Broadleaf weeds	▪ Hay or silage ▪ Silage ▪ Short, high intensity grazing ▪ Hay freezing	▪ High nitrogen rate ▪ Improved fertiliser placement ▪ High sowing rate
Oats – hay	High	Late	Late	▪ Grass – limited ▪ Broadleaf – many	▪ Brome grass ▪ Barley grass ▪ *Vulpia* spp. ▪ Annual ryegrass ▪ *Emex* spp.	▪ Strict guidelines for export	▪ Delayed sowing ▪ Double knock ▪ Post-cut knockdown ▪ Hay ▪ Hay freezing	▪ High sowing rate ▪ High nitrogen rate ▪ Improved fertiliser placement
Oats – grain only	Medium–high	Mid–late	Early–mid	▪ Grass – limited ▪ Broadleaf – many	▪ Wild oat ▪ Brome grass ▪ Barley grass ▪ *Vulpia* spp.	▪ Broadleaf weeds	▪ Delayed sowing ▪ Double knock ▪ Winter clean	▪ Long fallow ▪ High sowing rate ▪ Improved fertiliser placement
Triticale – grain only	Medium–high	Late	Late	▪ Grass – several ▪ Broadleaf – many	▪ Cereal rye ▪ Brome grass ▪ *Vulpia* spp.	▪ Broadleaf weeds	▪ Delayed sowing ▪ Double knock	▪ Long fallow ▪ Improved fertiliser placement ▪ Narrow row spacing
Triticale – graze and grain	High	Early–mid	Late	▪ Grass – several ▪ Broadleaf – many	▪ Cereal rye ▪ Brome grass ▪ *Vulpia* spp.	▪ Broadleaf weeds	▪ Double knock ▪ Short time, high intensity grazing	▪ Improved fertiliser placement ▪ High sowing rate ▪ High nitrogen rate
Wheat – early sown	High	Early	Mid	▪ Many	▪ Multiple-resistant annual ryegrass ▪ Barley grass	▪ Broadleaf weeds ▪ Wild oat ▪ Annual ryegrass	▪ Seed carts, chaff mills ▪ Burn residues	▪ Improved fertiliser placement ▪ Narrow row spacing ▪ High sowing rate
Wheat – main season	Medium–high	Mid	Mid	▪ Many	▪ Multiple-resistant annual ryegrass ▪ Barley grass	▪ Broadleaf weeds ▪ Wild oat ▪ Annual ryegrass	▪ Selective spray-topping ▪ Seed carts, chaff mills ▪ Burn residues	▪ Variety choice ▪ Improved fertiliser placement ▪ High sowing rate

[†] Presence of listed weeds severely limits use of crop type in a sustainable cropping system.
[‡] Highly suited tactics that can be used in addition to the traditional pre-sowing non-selective knockdown, pre-emergent residual herbicides and early post-emergent herbicides.

Crop	Competitive ability	Relative sowing time	Relative maturity	Available herbicide options	'NO GO' weeds †	Key weeds to target	Most suitable tactics other than pre- and post-emergent herbicide application	Agronomy to enhance weed management ‡
Wheat – quick maturing, short season varieties	Medium	Mid–late	Early	▪ Many	▪ Multiple-resistant annual ryegrass ▪ Barley grass	▪ Broadleaf weeds ▪ Wild oat ▪ Annual ryegrass	▪ Delayed sowing ▪ Autumn tickle ▪ Double knock ▪ Windrowing ▪ Seed carts, chaff mills ▪ Burn residues	▪ Improved fertiliser placement ▪ High sowing rate ▪ Narrow row spacing
Wheat – graze and grain	High	Early	Late	▪ Many	▪ Multiple-resistant annual ryegrass	▪ Broadleaf weeds ▪ Wild oat ▪ Annual ryegrass	▪ Short, high intensity grazing ▪ Burn residues	▪ Improved fertiliser placement ▪ High sowing rate ▪ High nitrogen rate
Wheat – durum	Medium	Mid–late	Early	▪ Many (tolerance limit with some herbicides)	▪ Multiple-resistant annual ryegrass ▪ Group A resistant wild oat	▪ Broadleaf weeds	▪ Delayed sowing ▪ Burn residues	▪ Improved fertiliser placement ▪ Narrow row spacing ▪ High sowing rate
Lucerne	High (density dependent)	N/A	N/A	▪ Limited for seedlings ▪ Several for mature stands	▪ Must use trifluralin for establishment – wireweed	▪ Grasses	▪ Spray-topping ▪ Winter cleaning ▪ Green/brown manuring ▪ Silage or hay ▪ Grazing management	▪ High phosphorus rate ▪ Good nodulation ▪ Variety choice
Subclover	Low–medium	Early–mid	N/A	▪ Several	▪ Bedstraw	▪ Grasses	▪ Spray-topping ▪ Green/brown manuring ▪ Silage or hay ▪ Grazing management ▪ Spray-grazing ▪ Wick/blanket-wiping	▪ Rotation ▪ High phosphorus rate ▪ Good nodulation ▪ Variety choice
French (pink) serradella (e.g. Cadiz)	Low–medium	Early–mid	N/A	▪ Grass – several ▪ Broadleaf – limited	▪ Bedstraw	▪ Grasses	▪ Hay-freezing	▪ Rotation

† Presence of listed weeds severely limits use of crop type in a sustainable cropping system.

‡ Highly suited tactics that can be used in addition to the traditional pre-sowing non-selective knockdown, pre-emergent residual herbicides and early post-emergent herbicides.

Crop	Competitive ability	Relative sowing time	Relative maturity	Available herbicide options	'NO GO' weeds †	Key weeds to target	Most suitable tactics other than pre- and post-emergent herbicide application	Agronomy to enhance weed management ‡
High density annual legumes (arrowleaf, berseem, Persian, sulla)	High if sown early low if sowing delayed	Early	N/A	▪ Limited		▪ Grasses	▪ Spray-topping ▪ Green/brown manuring ▪ Silage or hay ▪ Grazing management ▪ Spray-grazing ▪ Wick/blanket wiping	▪ Rotation ▪ High phosphorus rate ▪ Good nodulation ▪ Species and variety choice
Sorghum	Density dependent	Spring–summer	Variable	▪ Grass – limited ▪ Broadleaf – several	▪ Johnson grass (*Sorghum halepense*) ▪ *Sorghum almum* ▪ Feathertop Rhodes grass	▪ Winter grasses ▪ Summer broadleaf weeds	▪ Inter-row shielded spray or cultivation	▪ Variety choice ▪ Narrow row spacing ▪ High sowing rate ▪ Summer fallow ▪ No-till ▪ Summer/winter fallow
Sunflowers	Low	Spring – summer	Variable	▪ Grass – several ▪ Broadleaf – limited	▪ Burrs (*Xanthium* spp.) ▪ *Datura* spp. ▪ *Physalis* spp. ▪ Bladder ketmia ▪ *Ipomoea* spp. ▪ Parthenium weed and many summer broadleaf weeds	▪ Winter grasses ▪ Summer grasses	▪ Inter-row shielded spray or cultivation	▪ Rotation ▪ Summer/winter fallow
Mung beans	Low	Spring–summer	Early	▪ Grass – several ▪ Broadleaf – limited	▪ Burrs (*Xanthium* spp.) ▪ *Ipomoea* spp.	▪ Winter grasses ▪ Summer grasses	▪ Inter-row shielded spray or cultivation ▪ Wick/blanket-wiping	▪ Rotation ▪ Narrow row spacing ▪ High phosphorus rate ▪ Good nodulation ▪ Summer/winter fallow

† Presence of listed weeds severely limits use of crop type in a sustainable cropping system.

‡ Highly suited tactics that can be used in addition to the traditional pre-sowing non-selective knockdown, pre-emergent residual herbicides and early post-emergent herbicides.

2. Improving crop competition

Improving crop competition can improve weed control tactic effectiveness and reduce weed impact on crop yield. Key factors influencing a crop's competitive ability with weeds are the rate and extent of crop canopy development. A crop that rapidly establishes a vigorous canopy, intercepting maximum sunlight and shading the ground and inter-row area, will provide optimum levels of competition.

Canopy development can be influenced by:

- crop and variety
- row spacing, crop orientation, sowing rate and sowing depth
- crop nutrition
- foliar and root diseases and nematodes
- levels of beneficial soil microbes such as vesicular arbuscular mycorrhiza (VAM)
- environmental conditions including soil properties and rainfall.

Each will in turn affect plant density, radiation adsorption, dry matter production and yield. Early canopy closure can be encouraged through good management that addresses the factors above.

Crop type

The most competitive crop type will depend on the regional and individual paddock conditions, including soil type and characteristics (e.g. plant-available water, drainage, pH), rainfall and cropping history. Crop species or varieties that are susceptible to early insect or disease damage also become more susceptible to subsequent weed invasion and competition.

Choose a crop that suits the situation and, if possible, choose the most competitive variety. Generally, the best suited variety for the situation will also be the most competitive.

Key benefit

- A competitive crop improves weed control by reducing weed biomass and seed set

Sowing rate

The optimum plant density for each crop will differ with growing conditions, time of sowing and economic viability, so seek local advice. In unfavourable conditions (e.g. delayed sowing or poor soil conditions) growth of individual plants becomes limited, so higher plant densities may improve competitive ability and yield.

At any sowing time, increasing sowing rate can result in earlier crop canopy closure and greater dry matter production, improving weed suppression and the effectiveness of other weed management tactics.

Key benefits

- High crop sowing rates reduce weed biomass and weed seed production.
- Crop yield and grain quality may improve with increased sowing rates while benefiting weed control.

Key practicality

- If using higher sowing rates to improve competitive ability of a crop, remember to optimise the sowing rate for grain yield and quality potential.

Row spacing

Row spacing affects stubble handling ease at sowing and of controlling disease events in some crops. It also influences crop fertiliser use options. When all other factors are equal, narrow crop rows usually deliver much better crop competition than wider rows. However, wider row spacings may, in some instances, lead to more uniform crop establishment through more accurate seed and fertiliser measurement and placement. This can result in improved early vigour and, ultimately, increased crop competition. Summer crop (e.g. sorghum and sunflower) row spacing studies in Queensland have shown that as row spacing widened (greater than 1 m) crop yield penalty from uncontrolled weeds actually declined even though weed biomass and weed seed production increased.

Narrow row spacing to increase yield and reduce weed seed set

Source: Cox Inall Communications

Key benefit

- Increasing crop density increases weed suppression. In cereals higher crop densities can achieve further suppression if narrower row spacings are used.

Key practicality

- It is important to match row spacing and sowing rate to obtain crop plant densities that are optimal for both yield and competition against weeds.

Sowing depth

Maximum competitive ability will come from a crop sown at optimum and uniform depth to get rapid and uniform establishment.

Much of the yield loss from weed competition occurs in the first few weeks of crop growth. A crop with a few days' or one week's head start on weeds will be significantly advantaged. Sowing healthy seed (with a high germination rate) into ideal soil moisture at the optimal depth for establishment gives the crop a competitive advantage against weeds.

Optimum sowing depth for each particular soil type and crop type will vary. Achieving an optimum and uniform sowing depth will result in synchronous emergence, benefiting crop yield and improving crop competition.

Key benefit

- Sowing depth can be used to enhance crop competitive ability.

Key practicalities

- Use furrow sowing or moisture seeking techniques at sowing to establish the crop before the weeds.
- Take care to sow seed at optimum depth.

Sowing time

Time of sowing has a major effect on early crop vigour, canopy development, dry matter production and final yield, and all these factors have a direct impact on the competitive ability of a crop.

Delayed sowing reduces these factors, giving the weeds an advantage. Delaying sowing beyond the optimum window recommended in a given district will reduce early vigour, extend the time taken to reach canopy closure and reduce overall dry matter production. It is therefore important to sow within the recommended time period, not only to maximise yield but also to make the crop competitive.

Key benefit

- Sowing at the recommended time for the crop type and variety will maximise the competitive ability of the crop which, in turn, will reduce weed biomass and seed set.

Key practicalities

- When using delayed sowing to allow for control of the first germination of weeds, choose the crop type and variety most suited to later sowing to minimise yield loss.
- Sow problem weedy paddocks last to allow a good weed germination and subsequent kill prior to sowing.

Crop row orientation

The competitive ability of cereal crops can be increased by orientating crop rows at a right angle to the direction of sun light, that is, sow crops in an east-west direction. East-west crops more effectively shade weeds in the inter-row space than north-south sown crops. The shaded weeds have reduced access to photosynthetically active radiation (PAR) resulting in a reduction in biomass production and reduced seed set. Altering the orientation of a broadleaf crop has less impact on weed growth. This is because broadleaf plants will alter the angle of their leaves over the course of the day to 'track' the sun as it moves across the sky. Therefore, as the leaves of the broadleaf crop move to catch the most sunlight, they cast less shade over the inter-row space. Broadleaf crops are also slow to reach maximum canopy and therefore maximum light interception until late in the season allowing weeds to germinate and grow. Changing crop row orientation should be used as a part of an integrated weed management program and not seen as a 'stand-alone' tactic.

Key benefit

- Choosing an east-west orientation for cereal crops suppresses weed growth and may increase crop yield.

Key practicalities

- It is important to consider the weed species in the field.
- It is important to consider the layout and latitude (location) of the paddock to be sown.
- Using an east-west crop orientation may be more practical with auto-steer.

Soil properties

Crops growing in unsuitable soils are far more susceptible to disease and insect attack and can become more prone to damage from pre-emergent herbicides. Poor early vigour can also result from growing crops in unsuitable soils. When not actively growing, crop seedlings are unable to detoxify herbicide, which further reduces crop vigour and biomass. Slow crop growth is also advantageous to the weed. Nodulation of pulses can be reduced, thus decreasing plant biomass and competitiveness.

On very acidic soils (pH less than 4.5) grow narrow-leafed lupins, triticale or acid tolerant wheat as these are more suited to such soils than other crops. On heavy textured soils that suffer periodic waterlogging during early winter, the best-suited break crop is faba bean.

Sowing equipment should be tailored to suit soil properties to obtain the highest plant count in the shortest time. In heavy clay soils, presswheel pressure may need to be increased as the soil dries.

Improving soil constraints to plant growth (e.g. acidity, salinity, sodicity, boron toxicity) can dramatically improve crop growth. On an acidic soil in southern New South Wales the use of lime to ameliorate soil acidity resulted in suppressed weed growth and improved crop yields (Li and Conyers 2004. The period over which benefits will be returned depends on the amount of lime applied. Gazey and Andrew (2010) reported increased cereal yields at Kellerberrin in the Avon River Basin in Western Australia up to 17 years after lime was applied at 2.5 t/ha or more. The optimum rate of 5 t/ha of lime for the tenesol soil could be applied in a single operation, or through several applications over a number of years.

Key benefit

- Matching the crop (and variety) to the soil type can improve crop vigour and biomass production, which in turn will optimise crop competitive ability.

Fertiliser use and placement

Macronutrients including nitrogen (N), phosphorus (P), potassium (K), sulphur (S), calcium (Ca) and magnesium (Mg) are most important for plant growth. Ensure that these nutrients are in good supply before considering micronutrients such as copper (Cu), zinc (Zn), manganese (Mn), iron (Fe), molybdenum (Mo), boron (B) and chlorine (Cl). In some locations there may be known deficiencies of some micronutrients that need to be addressed for either good plant growth or subsequent animal growth. For example, cobalt (Co) and selenium (Se) are deficient in southern Western Australia and Mo is deficient in the ironstone soils of Tasmania (Peverill et al 1999).

Key benefit

- Matching fertiliser inputs of both macro- and micro-nutrients to crop target yield and quality will maximise the crop's competitive ability against weeds.

Key practicality

- Fertiliser placement can improve crop growth, yield and competitive ability.

Disease and insect pest management

One of the key strategies for managing diseases and insect pests is enterprise sequencing. It is well known that annual and some perennial grasses are hosts for some root diseases and a significant grass-free period is required to reduce these pathogens before cereals should be grown. A range of other pathogens is also carried between seasons on crop residues.

Key benefit

- Preventing and/or controlling crop disease and insect damage maximises crop health and competitive ability, avoiding blow-outs in weed seed production.

Key practicality

- Monitor crop health and control pests and diseases.
- Areas of crop death (or weakness) become a haven for weeds to proliferate.

3. Herbicide tolerant crops

Herbicide tolerance and other genetic traits such as disease resistance are introduced into crops in two ways: either by conventional breeding methods or by genetic modification, which is the introduction of genes from another organism.

Crops herbicide tolerance traits bred using conventional methods have been used in Australia for some years. For example, triazine tolerant (TT) canola was first used in commercial production in 1994 and imidazolinone tolerant (IT) wheat was introduced in 2001. Genetically modified
(GM) herbicide tolerant (HT) cotton has been commercially grown in Australia since 2000, while Roundup Ready® canola was first commercialised in some states in 2008.

HT crops are tolerant to a herbicide that would normally cause severe damage. One example is the Group B imidazolinone herbicide used in Clearfield® canola cultivars where these crops have been conventionally selected and bred for tolerance to this herbicide. Roundup Ready (RR) is the name given to cultivars that have been bred using GM technology which include a gene that provides the cultivar with tolerance to the herbicide glyphosate. Cultivars without these traits would be killed or severely damaged.

Herbicide tolerant canola growing at Forbes, NSW.
Source: GRDC

HT crops can offer weed control tactics from different herbicide mode of action (MOA) groups than would normally be used in these crops. Growing HT crops can simplify weed control practices and in some instances lead to lower herbicide use.

With the ease and high levels of weed kill often experienced with glyphosate use in RR crops, the frequency of use of other control tactics has declined. Diversity in weed management tactics has decreased and selection pressure for glyphosate resistance development has increased. In an attempt to offset this, many of the stewardship packages associated with HT technologies require the use of alternative technologies in situations where weed density or resistance risk to a particular herbicide is high.

Key benefits

- Herbicide tolerant crops provide additional crop choice, enabling the use of alternative weed management tactics to target specific weeds while maintaining crop sequences.
- Herbicide tolerant crops can be grown where herbicide residues may be present in the soil from a previous crop
- Herbicide tolerant crops can reduce the total amount of herbicide used and weed control costs.

Key practicalities

- Always use HT crops as part of an integrated weed management program.
- Ensure the user is aware of, and adheres to, stewardship agreement restrictions placed on the ‘frequency of use’ of herbicides within MOA groups.
- Use technologies and weed management strategies that are appropriate to the weed spectrum and pressure.
- Adhere to all herbicide label directions. Not all HT crops are tolerant at all growth stages
- Good paddock management records must be kept, referred to and be accessible whenever required.
- Use agronomic practices to minimise out-crossing (hybridisation) to other crops.

4. Improving pasture competition

Pastures represent an important component of many rotations and can range from one to five years' duration to break up extended periods of cropping. Incorporating pastures can help restore soil fertility (i.e. organic matter and soil nitrogen) that may have declined due to frequent cropping and, in turn, improve the competitive ability of crops.

Pastures provide a valuable opportunity to manage weed problems using tactics that can not be used in cropping situations, such as grazing, mechanical manipulation and non-selective herbicides.

Key benefits

- Dense stands of well-adapted pasture species compete against weeds, reducing weed numbers and weed seed set.
- Competitive pastures greatly improve the effectiveness of other tactics used to manage weeds in the pasture phase.

Key practicalities

- Select species and varieties to suit your conditions.
- Once a pasture gets below a threshold density for a desirable pasture species it should be manipulated to build up seed reserves, or reseeded with improved cultivars.
- Mixtures of pasture species will add diversity to the pasture base and improve the capacity for desirable plants to fill gaps created by disturbance (e.g. drought, cropping).

5. Fallow phase

Fallows are defined as the period between two crops, or between a crop and a defined pasture phase, where the objective is to store and conserve soil water and nitrogen for the next crop and reduce the weed seedbank. The term 'fallow' has different meanings in different parts of Australia.

There are five broad categories:

1. In a winter rainfall (southern) continual cropping sequence of two or more crops, the period between the harvest of one crop and sowing of the next crop represents the shortest fallow period. This is typically about four months. Since the short fallow commences after harvest, it has no impact at all on the previous winter-growing weed seed production. In wet summers, summer-growing weeds can be controlled but this has no direct in-crop weed management benefits in a winter cropping sequence, other than reduced nutrient tie-up, improved moisture accumulation and better sowing conditions through the killing of vine-forming weeds such as melons (*Citrullus* spp. and *Cucumis* spp.) and wireweed (*Polygonum* spp.).
2. In a winter rainfall (southern) pasture–crop sequence the period between killing the pasture (this is usually August to September but it can be earlier) and sowing the first crop would be thought of as a long fallow and would last about eight months. Because such fallows should start well before weed seed maturity, they are an ideal opportunity for weed seedbank management.
3. In northern areas of New South Wales and southern Queensland where rain-fed summer crops can be grown, fallow periods exist between winter cereal harvest and the sowing of a summer crop (e.g. sorghum), or roughly December through to the following October, a period of around 10 months. Similarly, a fallow can exist between sorghum harvest (about March) through to cereal sowing in the following year (about May to June), a period of around 14 months.

Weed-free summer fallows can preserve water and nitrogen for the next crop.
Photo: Brad Collis

4. In low rainfall environments some farmers opt to ‘skip a year’ and call this a long fallow. Harvest would take place in November of Year 1 and sowing would not occur again until April to May of Year 3, a period of about 18 months. These long fallows include both a winter and summer growing season. The winter growing season presents a valuable management opportunity for winter-growing weeds. Similarly, the summer season offers weed management options for summer-growing annual weeds. However, this type of fallow opens the system to high erosion risk, particularly if stubble covers are low.
5. In northern cropping systems it is also common to have consecutive winter-growing crops, depending on available subsoil moisture. As in category 1 above, the fallow period between these crops is about six months and has no impact on winter-growing weed species. Since it includes a summer period, a short northern fallow will have an impact on summer-growing annual weeds.

Key benefits

- A fallow period on its own, or in sequence with a number of crops, can be highly effective in reducing weed seed numbers in the soil seedbank.
- A fallow period can incorporate a number of tactics to reduce weed seedling and seedbank numbers.
- A doubleknock of glyphosate followed three to 10 days later with paraquat (depending on the situation) gives high levels of weed control and controls any hard-to-kill or glyphosate resistant survivors.
- Under carefully planned conditions it is possible to use other herbicide MOA groups (Groups C, B, I or K) in fallow.
- In a fallow phase it is easier to judge weed control tactic efficacy as there should be no surviving weeds
- Soil moisture will be conserved.
- Available nutrient levels will be optimised
- Fallow paddocks can provide fire protection for farms and livestock. Stubble-free fallows provide a safe refuge for stock during bushfires.

A review of summer fallow practices and weed control in 2014 by John Cameron and Mark Congreve identified a number of benefits of fallow weed control. Stopping weed growth in the fallow can lead to yield increases in the following crop via several pathways. These include:

- Increased plant available water
- A wider and more reliable sowing window
- Higher levels of plant available N
- Reduced levels of weed vectored diseases and nematodes
- Reduced levels of rust inoculum via interruption of the green bridge
- Reduced levels of diseases vectored by aphids that build in numbers on summer weeds, and
- Reduced weed physical impacts on crop establishment.

Key practicalities

- Control fallow weeds when they are small.
- Avoid over-reliance on cultivation.
- Rotate herbicide MOA groups.
- Residual herbicides may be used for managing fallow weeds.
- Avoid cultivating wet soil.

6. Controlled traffic farming or tramlining

Controlled Traffic Farming (CTF) refers to a cropping system designed to limit soil compaction damage by confining all wheel traffic to permanent lanes for all field operations, including seeding, harvesting and spraying activities.

Soil compaction between the tramlines is greatly reduced, resulting in increased crop health. This form of precision agriculture results in several potential benefits for weed management, namely:

- more efficient pesticide application use due to reduced overlaps
- greater ability to access the field if soil is wet for timely spray application
- ability to treat weeds in the inter-row more easily
- additional options for managing weed seeds at harvest.

Key benefits

- Accurately spaced tramlines provide guidance and a firmer pathway for more timely and accurate herbicide application, improving weed control and reducing input costs.
- Precision guidance in wide-row cropping systems adds potential for new physical and chemical weed management options.
- Complete controlled traffic farming avoids wheel compaction of the crop zone, resulting in a more competitive crop.

Key practicalities

- Tramlines can be installed relatively cheaply, with immediate economic benefits gained from more accurate field operations with less overlap.
- Tramlines may be moved to minimise erosion and prevent concentration of nutrients, but future machinery may be capable of spreading residue evenly for even nutrient distribution.

Study has shown that tramlining reduces fuel and fertiliser use.
Photo: GRDC

TACTICS – MANAGEMENT OF WEEDS USING TACTIC GROUPS

Integrated weed management in Australian cropping systems approached weed management in a novel manner by introducing the concept of Tactic Groups. This concept creates new options and opportunities for weed management and has been designed to change the focus of growers and advisers from crop yield to weed life cycle.

Individual weed management tactics are packaged into tactic groups according to the target growth stage of the weed. The tactic groups are based on the five key objectives of all weed control strategies (see table below):

Tactic group	Aim
1. Deplete seedbank	Deplete weed seed in the target area soil seedbank.
2. Kill weeds	Kill weeds/seedlings in the target area.
3. Stop seed set	Stop weed from setting seed.
4. Stop adding to the seedbank	Prevent viable weed seeds within the target area being added to the soil seedbank.
5. On farm hygiene	Prevent introduction of viable weed seed from external sources.

In a well-integrated weed management plan each target weed will be attacked by a number of tactics, each from a different tactic group. They should be combined in the same way herbicides from different MOA groups are rotated. Integrating tactic groups and MOA groups will reduce weed numbers, stop replenishment of the seedbank and minimise the risk of developing populations of herbicide resistant weeds.

When selecting a tactic, consider the aim of the group to which each tactic belongs, and evaluate the suitability of the activity to the target weed and the weed's growth stage. Some weed management tactics such as manuring significantly reduce crop production or yield, often producing a dramatic reduction in gross margin for that paddock. Instead of excluding such tactics, consider the option of using them as a one-off solution in problem situations. Tactics used in this way can be highly effective, reducing weed seedbank numbers by up to 95% in a single year.

Knowing the problem that is to be faced is essential to solving the weed management dilemma.

1. Deplete seedbank

Burning residues

Despite summer fires being able to effectively destroy the surface seedbanks of many weeds, including annual ryegrass (*Lolium rigidum*), the environmental hazard of burning at this time of the year in Australia is extreme (Gill and Holmes 1997) and therefore illegal.

Autumn burns are an effective alternative and have been shown to successfully decrease weed seed densities. Strategic late burning (in March) to manage weed seedlings and surface weed seeds is therefore useful for growers on soils with low erosion potential.

Crop residue burning may challenge the stubble retention principles of many grain growers and advisers. However, when used strategically as a one-off tactic and in conjunction with other management strategies, it can be quite effective in reducing viable weed seed numbers.

Key benefit

- Burning can reduce viable weed seed numbers in the seedbank.
- Combining burning with other tactics (e.g. seed collection or narrow header trails) will increase the overall weed control impact.
- Late autumn burning of crop residues can kill weed seedlings.
- Burning can stimulate weed germination of some weed species for subsequent control with another tactic.
- Burning removes residues and thereby allows more effective incorporation of pre-emergent herbicides.

Key practicalities

- A high temperature burn will achieve the best result, accounting for seasonal risks
- Prepare the burn area to ensure best placement of seeds.
- Time burning to suit residue conditions and legislative limitations.
- Burning effectiveness depends on residue placement and quantity.
  Burning is not a suitable tool to manage all weed species.

Whole-farm considerations

The benefits of burning for weed management must be weighed up against a number of concerns. These include:

- environmental concerns about pollution and carbon dioxide emissions from burning crop residues
- potential respiratory health issues (e.g. asthma)
- soil erosion risk following burning, especially after a total residue burn
- adverse effects on soil fertility, organic matter and soil structure, especially if burning is used frequently
- reduced soil water infiltration and increased evaporation and run-off due to crop residue removal
- reduced numbers of macro- and micro-organisms, especially earthworms, and therefore reduced biopores
- a shortened sowing window after rain.

In the past grain growers across Australia have regularly used crop residue burning so they understand the following practicalities associated with the tactic:

- Burning must be conducted following state rural fire service regulations.
- Chaff dumps can take a long time to burn, creating smell and smoke issues. Extended burning time also heightens fire risk.
- Legislation to ban burning has been introduced in some countries around the world due to concerns over greenhouse gas emissions, global warming and health issues.
- There is public pressure in Australia to ban burning, especially in areas in close proximity to large urban centres.

Encouraging insect predation of seed

The contribution that insects make to seedbank reduction is often overlooked, despite weed seeds comprising a major component of many insect diets. This seed predation is often termed ‘natural mortality’ to partly explain why less seed is returned to the seedbank than is produced. Minimum and zero tillage increases ants and other invertebrate populations which encourages predation. Experiments conducted in WA by Evans and Gleeson (2016) showed that in a natural dispersed environment, ants were capable of reducing weed population. These results and other studies suggest that ants may be a useful component of an integrated weed management program.

Understanding the role that insects play in removing weed seeds could potentially help develop farming systems that encourage greater seed removal from the seedbank. A range of invertebrates (such as ants and carabid beetles) and vertebrates (birds and rodents) are significant post-dispersal weed seed predators (Wu 2015). In NSW seed theft by ants has commonly caused pasture failure, so it is feasible that weed seedbanks also could be decreased by encouraging ant predation.

Key benefit

Insect predation can reduce seedbank numbers. Predation levelscan be quite variable, with removal rates ranging from 0 to 100% depending on seedbank proximity to ant colonies. Ants were responsible for reducing weed numbers by 50% in WA studies in 2006 (Evans and Gleeson, 2016). Predation by insects was found to be significantly higher for annual ryegrass (*Lolium rigidum*) seed than wild radish (*Raphanus raphanistrum*) seed in a study in the WA wheatbelt. Three months into the study 81% of the original annual ryegrass seed had been removed, compared to 46% of wild radish seed.

Key practicality

- Predation levels tend to be higher in locations in near 'refuge'.
- Predation can be maximised by avoiding the overuse of broad spectrum insecticides.
- Manage stubble according to the type of seed predator present.
- Minimum tillage improves weed seed predation.
- Soil disturbance over summer reduces seed predation.

Inversion ploughing

Inversion ploughing is used to fully invert the soil to ensure that weed seeds that were on or just below the soil surface are placed at a depth from which they cannot germinate. This can be practised every 10 to 15 years without detrimental effect to the environment, where zero or reduced tillage is used in the intervening years. This timeframe is required for weed seeds to die and non-wetting waxes to break down. Inversion ploughing is particularly effective at resetting the weed seedbank and is very useful if herbicide resistant weeds are a problem.

Inversion ploughing has been adopted in Western Australia using commercial two-way machines, a modified mouldboard plough with skimmers to assist with total soil inversion. The technique is used after the season break when the soil profile is wet to a depth of at least 40 cm. More up to date information is available on the WeedSmart website. https://weedsmart.org.au/?s=inversion+ploughing

Trials have shown yield increases following inversion ploughing.
Photo: Stephen Davies

Key benefit

In suitable soil types, weed seed burial is an effective way to kill weed seeds.

Key practicalities

- Soil inversion is most effective in reducing seedbank numbers of weeds with limited dormancy.
- Appropriate soil type is needed for effective soil inversion.
- Inversion ploughing of moist soil followed by the immediate sowing of a crop will reduce wind and water erosion risk.
- Mouldboard ploughs must be operated and set up correctly to achieve total inversion.
- Occasional inversion ploughing is unlikely to damage to soil structure.

Whole-farm benefits

Additional benefits from inversion ploughing include:

- disease and insect control due to the burial of stubble
- amelioration of non-wetting soils
- nitrogen mineralisation
- removal of any nutrient stratification in the soil (i.e. mixing of nutrients concentrated in one layer of the soil, usually the surface)
- opportunities for soil ameliorant (e.g. lime) application at depth.

Autumn tickle

Autumn tickling (also referred to as an ‘autumn scratch’ or shallow cultivation) stimulates weed seed germination by placing seed in a better physical position in the soil (Gill and Holmes 1997). At a shallow depth of 1 to 3 cm the seed has better contact with moist soil and is protected from drying. Because weeds that germinate after an autumn tickle can be controlled, this process will ultimately deplete weed seed reserves.

A range of equipment can be used to conduct an autumn tickle including tyned implements, skim ploughs, heavy harrows, pinwheel (stubble) rakes, dump rakes and disc chains.

Tickling can increase the germination of some weed species but has little effect on others. Tickling needs to be used in conjunction with delayed sowing for the greatest opportunity to control emerging weeds and deplete the seedbank.

Key benefit

- A well-timed autumn tickle will promote earlier and more uniform germination of some weed species for subsequent control.

Key practicalities

- Autumn tickle should be used in conjunction with another tactic.
- Success of autumn tickling depends on environmental conditions before and after implementation.
- Soil type is critical for a successful autumn tickle.
- Use autumn tickling in non-crop situations to stimulate germination of weeds which can then be managed with grazing or a non-selective herbicide.
- The efficacy of an autumn tickle will vary with weed species.

Whole-farm considerations

Determine the suitability of autumn tickle as a weed management tactic by considering the following points:

- Soil disturbance before sowing can reduce soil moisture, placing the sowing operation at risk in a dry season.
- Soil disturbance before sowing can incorporate stubble and, as a result, significant amounts of soil nitrogen will be tied up by microbes that proliferate to degrade the stubble.
- In the early stages of no-till adoption, short-term nitrogen deficiencies are likely if stubble levels are high.

Delayed sowing

Delayed sowing (seeding) is the technique of planting the crop beyond the optimum time for yield in order to maximise weed emergence. Weeds that emerge in response to the break in season can then be killed using a knockdown herbicide or cultivation before crop sowing.

This tactic is most commonly employed for paddocks that are known to have high weed burdens. Paddocks with low weed burdens are given priority in the sowing schedule, leaving weedy paddocks until later. This allows sufficient delay for the tactic to be beneficial on the problem paddock without interrupting the whole-farm sowing operation.

Choosing a crop or cultivar with a later optimum sowing time can reduce the risk of reduced yield.

Key benefits

- Delayed sowing can dramatically reduce early crop competition and deplete the weed seedbank.
- Delayed sowing is very effective when used in conjunction with additional weed management tactics.

Key practicalities

- Target problem paddocks first.
- When planning to delay sowing in a problem paddock, choose a crop or variety that is suited to later sowing in order to reduce the risk of yield loss.
- Seasonal conditions will influence delayed sowing opportunities.

2. Kill weeds (seedlings)

Fallow and pre-sowing cultivation

Cultivation, as a function of fallowing and pre-sowing operations, can kill many weeds including herbicide resistant populations. It is useful as a one-off tactic in reduced tillage or no-till operations, and can be used as a non-herbicide component of a 'double knock' system.

Key benefits

- Well-timed cultivation effectively kills weeds.
- In preparing a seedbed, cultivation provides a weed-free environment for the emerging crop.
- Cultivation can control weeds in situations where herbicides are ineffective or not an option.
- Pre-sowing cultivation or full disturbance cultivation at sowing reduces the reliance on knockdown herbicides and therefore the likelihood of weed populations developing herbicide resistance.
- Incorporating soil ameliorants (e.g. lime or gypsum)
- Overcoming nutrient stratification
- Breaking up a plough pan
- Pupae busting (e.g. breaking the life cycle of *Helicoverpa* spp. in cotton cropping systems).

Key practicalities

- Strategic cultivation must take into account whole-farm practicalities.
- Maintain soil structure by cultivating at suitable soil moisture levels and appropriate implement ground speed.
- The tillage implement used will influence the level of soil disturbance and thereby the effect on the weeds present.
- Choice of cultivation practice can influence weed density and spectrum.

Whole-farm considerations

Cultivation reduces surface stubble cover that would otherwise be maintained for as long as possible to reduce erosion risk and optimise soil moisture storage.

The type of seedbed produced by cultivation will depend on soil type and moisture content. Poorly timed cultivation, resulting in a poor seedbed, can lead to reduced crop emergence, herbicide damage and reduced herbicide performance.

Pre-season cultivation may improve the reliability of sowing time in some environments. In low rainfall environments pre-season cultivation may delay sowing.

Over-reliance on cultivation can:

- reduce soil cover from plant residues
- degrade soil structure
- reduce available soil water.

Knockdown (non-selective) herbicides for fallow and pre-sowing control

Knockdown herbicides lack species selectivity and therefore kill all plants when used in sufficient quantities under suitable spraying conditions. For this reason knockdown herbicides are used to control a wide range of weeds, either in a fallow or before sowing.

To simplify weed management certain crop cultivars (e.g. Roundup Ready® crops) have been developed to tolerate some knockdown herbicides.

Key benefits

- Knockdown herbicides are effective and cost-effective.
- Use of knockdown herbicides can improve the timeliness of sowing.

Key practicalities

- Overuse of a knockdown herbicide will select for weed populations that are resistant to that particular herbicide.
- Consider the suitability of knockdown herbicides for fallow or pre-sowing weed control by assessing environmental conditions.
- Stressed weeds will not be adequately controlled by knockdown herbicides.
- Suitable meteorological conditions for spraying can be limited, especially in summer.

Double knockdown or 'double knock'

'Double knock' refers to the sequential application of two different weed control tactics applied in such a way that the second tactic controls any survivors of the first tactic. Most commonly used for pre-sowing weed control, this concept can also be applied in-crop.

The double knock approach to weed management was first used in the 1960s when direct drilling was still developing. The system comprised an application of knockdown herbicide (paraquat or paraquat/diquat) followed by full disturbance sowing.

Other double knock strategies include non-selective herbicide application followed by burning or grazing. Although these combinations of tactics are still valid today, the trend towards no-till farming, with minimal disturbance sowing and often with wider crop rows, has led to the double knockdown technique.

The double knockdown technique is the sequential application of two knockdown herbicides from different MOA groups, such as glyphosate (Group M) followed by paraquat/diquat (Group L), at an interval of between one and 14 days. Used before sowing, each herbicide in the double knockdown must be applied at a rate which would be sufficient to control weeds if it was used singularly. The second herbicide is applied with the aim of controlling any survivors of the first herbicide application. Control of weeds that germinate during the interval between the two herbicide applications is an incidental benefit.

It is important to understand that the double knockdown method is definitely not two sequential applications of the same knockdown herbicide. While this practice is used occasionally when there are a number of pre-sowing germination events, it does not include the key characteristic of minimising selection pressure for resistance.

Although double knockdown has primarily targeted annual ryegrass (*Lolium rigidum*) it is an effective tactic for use on a wide range of weed seedlings.

Key benefits

- Double knockdown delays or prevents glyphosate resistance development
- Using a double knockdown or double knock strategy reduces the number of glyphosate resistant weeds to be controlled in-crop.
- Excellent weed seedling control is obtained by using a pre-sowing double knockdown.

Key Practicalities

- Glyphosate should be applied first, followed by paraquat or paraquat/diquat.
- The time between applications will vary with the main target weed species
- Identify the weed species being targeted.
- Apply the first herbicide when the weeds are most likely to be killed.
- Double knockdown is more expensive than a single herbicide application.
- Seasonal conditions and spraying capacity will influence the scale of on-farm implementation.

Pre-emergent herbicides

Pre-emergent herbicides control weeds at the early stages of the life cycle, between radical (root shoot) emergence from the seed and seedling leaf emergence through the soil.

Of the 19 herbicide MOA groups, 12 are classed as having pre-emergent activity.

Pre-emergent herbicides may also have post-emergent activity through leaf absorption and can be applied to newly emerging weeds. For example, metsulfuron methyl is registered for control of emerged weeds but gives residual control typical of many pre-emergent herbicides. There are also herbicide treatments that are solely applied pre-emergent (e.g. trifluralin).

Key benefits

- The residual activity of a pre-emergent herbicide controls the first few flushes of germinating weeds (cohorts) while the crop or pasture is too small to compete.

Key Practicalities

Good planning is needed to use pre-emergent herbicides as an effective tactic. Soil characteristics and environmental conditions at the time of application play an important role in the availability, activity and persistence of pre-emergent herbicides:

- soil texture
- soil pH
- organic matter
- previous herbicide use
- soil moisture
- initial application rate
- soil temperature
- volatilisation
- photodegradation.

Selective post-emergent herbicides

Selective post-emergent herbicides control weeds that have emerged since crop or pasture establishment and can be applied with little damage over the top of a crop or pasture.

The first selective post-emergents to be developed were the Group I MOA herbicides and the first 'modern' herbicide, 2,4-D, became commercially available around 1945. Western industrialised agriculture changed with the release of Group A and B herbicides in the late 1970s.

Selective post-emergent herbicides belong to herbicide MOA Groups A (e.g. diclofop), B (e.g. metsulfuron), C (e.g. diuron), F (e.g. diflufenican), G (e.g. carfentrazone), I (e.g. 2,4-D, dicamba, picloram), J (e.g. flupropanate), R (e.g. asulam) and Z (e.g. flamprop). Some predominantly pre-emergent herbicides also have registrations for some selective post-emergence activity, e.g. dithiopyr (Group D) and chlorpropham (Group E).

Key benefits

- Post-emergent herbicides give high levels of target weed control with the additional benefit of improved crop or pasture yield.
- Observations made just before application allow fine-tuning of herbicide selection to match target weeds present in the paddock.
- Timing of application can be flexible to suit weed size, crop growth stage and environmental conditions.
- Some post-emergent herbicides have pre-emergent activity on subsequent weed germinations.

Key Practicalities

- Use careful consideration when selecting the best post-emergent herbicide to use in any one situation.
- Applying post-emergent herbicides to stressed crops and weeds can result in reduced levels of weed control and increased crop damage.
- Crop competition is important for effective weed control using selective post-emergent herbicides.
- The technique used for applying selective post-emergent herbicides must be suited to the situation in order to optimise control.
- Always use the correct adjuvant to ensure effective weed control.
- Selective post-emergent herbicides applied early and used as a stand-alone tactic have little impact on weed seedbanks.
- Choose the most suitable herbicide formulation for each particular situation.
- Selective post-emergent herbicide effectiveness is influenced by a range of plant and environmental factors.
- Match herbicide mode-of-action (MOA) to its use.

Weed control in wide-row cropping

In northern NSW and QLD wide-row cropping has been used for some years as a way to improve yield reliability in grain sorghum production. Wide rows are also used in wheat and chickpea cropping in central Queensland to improve stubble handling and moisture seeking abilities of sowing operations (Reid et al 2004).

Wide-row cropping has also been widely adopted in Western Australia as a strategy to overcome herbicide resistant wild radish (*Raphanus raphanistrum*) and, to a lesser extent, annual ryegrass (*Lolium rigidum*).

In response to escalating herbicide resistance and to maintain cropping programs, growers and researchers are developing shielded spraying tactics for wide-row winter crops. This tactic uses non-selective (knockdown) herbicides to control weeds in the inter-row space of the crop. In some circumstances inter-row cultivation may be applicable.

Inter-row cultivation, band spraying and, to a lesser extent, shielded spraying are not new techniques. The innovation is to use them in winter growing broadacre crops.

Pulse crops have been the initial driver and subsequent emphasis for much of the wide-row research aimed at herbicide resistance management across Australia. The wide-row planting configuration has a distinct advantage, particularly when using non-selective herbicides for inter-row weed control. Using the tactic in only one part of the crop rotation avoids excessive use of the knockdown herbicide, thus reducing the risk of herbicide resistance development.

Key benefits

- Increasing row spacing allows improved weed control while maintaining or improving crop yield.
- Cropping in wide rows enables the use of shielded inter-row herbicide application, crop-row band spraying and inter-row cultivation for in-crop weed control.

Key Practicalities

- Reduced competition from the crop can result in lower yield potential if weeds are not controlled.
- A change to wide rows will require modifications to sowing equipment, a complete change in equipment or use of a contractor.
- Precision farming technologies fit well with wide rows for weed management.

Whole-farm benefits

- Wide-row cropping enables increased quantities of crop residues to be retained, thus reducing the potential for erosion and improving soil characteristics.
- Wide-row cropping enables easier sowing into retained crop residues.
- There is an option to use smaller tractors with less tynes per sowing width, thus reducing costs.
- Wide rows can reduce crop foliar fungal disease incidence by allowing better airflow within the crop canopy.
- Wide rows work well with tramlining and controlled traffic farming, adding benefits associated with reduced soil compaction and more accurate and timely application of inputs.
- Wide-row cropping provides opportunities for precision fertiliser placement such as side dressing.

Inter-row shielded spraying and crop-row band spraying

The trend towards wide-row planting for a range of crops risks greater reliance on herbicide control to balance declining crop competition. This in turn poses serious problems for herbicide-resistant weed development and management. Research with resistant weed populations (Storrie, unpublished) has shown that inter-row spraying with lower risk herbicides is a useful tool for managing resistant or hard-to-kill weeds. However, this practice increases the herbicide resistance risk to those herbicides being used and needs to be carefully managed.

Despite farmers seeing benefits in inter-row spraying using shields with knockdown herbicides and trialling a range of techniques, its use at time of writing is limited to glyphosate in cotton and paraquat in row crops.

Key benefits

- Shielded spraying allows inter-row application of non-selective herbicides in-crop, which can increase crop yield.
- Band spraying reduces the risk of herbicide resistance development by limiting the application of higher risk selective herbicides over the crop row.

Key Practicalities

- Timing of shielded spraying is important.
- Care must be taken with the set-up and operation of shielded sprayers to minimise spray drift. All shields leak spray drift to some extent.

Lupins grown in wide rows sprayed with a shielded boom allowing herbicide to be applied between the rows.
Photo: GRDC

Inter-row cultivation

Key benefit

- Inter-row cultivation provides an opportunity to control weeds without herbicides.

Key practicalities

- Inter-row cultivation timing is critical to ensure maximum levels of weed control with minimal damage to the crop.
- Weed control is reduced if the soil is too wet or weed densities are too high.
- Heavy stubble cover may preclude inter-row cultivation.
- Inter-row cultivation does not control weeds in the crop row, so an additional tactic must be used for the crop-row weeds.
- Inter-row cultivation cannot be used in conjunction with ground covering stubble mulch techniques.
- Inter-row cultivation can stimulate emergence of some weed species.

Spot spraying, chipping, hand roguing and wiper technologies

Where new weed infestations occur in low numbers eradication may be possible. In such situations more intensive tactics to remove weeds can be used in addition to ongoing management tactics which aim to minimise weed impact. The term 'wiper technologies' refers to the many versions of wipers available (e.g. wick wipers, rope wipers, carpet wipers, weed wipers).

Key benefit

- Vigilance and attention to detail can be the difference between eradication and a prolonged and costly problem.

Key Practicalities

- Instigate accurate future monitoring by marking isolated infestations.
- Isolate the infested area to reduce the risk of further spread.
- Controlling new weed infestations and low density weed populations requires only simple measures.
- Timing of control is important to avoid seed set.

Weed detector sprayers

Weed detector sprayers are low volume spot spraying technology for the control of scattered weeds in crop fallows. The 'weed detector-activated' sprayer consists of detector units mounted to a boom which detect weed presence using infra-red reflectance. When each individual unit passes over a weed it activates a solenoid which in turn switches on an individual even-fan nozzle, spraying the weed.

There are provisions, when targeting weeds larger than 10 cm in diameter, to use higher herbicide rates per hectare compared with normal 'broadcast' boom spraying. Despite this, the technology is currently reducing the per hectare fallow spray application rates by 80 to 95% depending on the density of the fallow weeds.

Key benefits

- Only 10 to 15% of the field is being treated, reducing fallow management costs and encouraging higher levels of weed control.
- A range of herbicide mode-of-action (MOA) can be used to combat herbicide resistance.
- Using a weed detector sprayer reduces the risk of herbicide drift.
- Using a weed detector sprayer enables spraying in the evening.

Key Practicalities

- Weeds must be large enough to be detected.
- Travel speeds are limited
- Strong winds can reduce coverage and control.

Biological control

Biological control (or 'biocontrol') for weed management uses the weed's natural enemies (biological control agents). These natural enemies include herbivores such as insects, but also include sheep where there is direct consumption of the weed. They also include micro-organisms such as bacteria, fungi and viruses which can cause disease, change weed vigour and competitiveness relative to the crop and decay the weed seed in the seedbank. Other plants which can be included under biological control are those which release substances that suppress weed growth (known as 'allelopathy').

Key benefits

- The effectiveness of biological control can be increased when used in conjunction with other methods.
- Biocontrol agents, particularly bioherbicides, have an advantage over chemical herbicides in situations where the latter may be ineffective (e.g. due to herbicide resistance) or inappropriate (e.g. near sensitive wetlands or in organic agriculture).

Key Practicalities

- The biology of the weed influences how well a classical biocontrol agent will work.
- Success is dependent on the existence of suitable agents and their degree of host specificity.
- Bioherbicide technology is limited by the need for a large-scale market to make the product viable and by environmental constraints.

3. Stop seed set

Seed set control tactics include spray-topping with selective herbicides, crop-topping with non-selective herbicides, wick wiping, windrowing and crop desiccation, and techniques such as hand roguing, spot spraying, green and brown manuring, hay and/or silage production and grazing. These tactics can be loosely termed 'seed kill' tactics because each aims to reduce weed seed production. The goals are to reduce the weed seedbank, obtain future benefits from depleted weed populations and reduce grain contamination. Weed seed set management is most applicable to weeds that are expensive to control and/or resistant to herbicides and when weed densities are low. Seed set control tactics are particularly effective when weed populations have already been reduced to low levels through fallowing, pasture or other specific crop rotation or weed management practices.

Key benefits

- Using in-crop weed seed set control tactics can dramatically reduce future expenditure on weed management.
- In-crop seed set control reduces weed seed contamination levels in grain samples at harvest.

Key Practicality

- Plan weed seed set management in advance.

Spray-topping with selective herbicides

Selective spray-topping applies a post-emergent selective herbicide to weeds at reproductive growth stages to prevent seed set of certain weeds. The technique is aimed at weed seedbank management (i.e. reducing additions to the weed seedbank) but with minimal impact on the crop.

Selective spray-topping is suited to a crop situation and largely targets broadleaf weeds (especially brassica weeds). The tactic should not be confused with pasture spray-topping which occurs in a pasture phase, involves heavy grazing, uses a non-selective herbicide and largely targets grass weeds.

The strategy can be used to control 'escapes', as a late post-emergent salvage treatment or for managing herbicide resistance.

The rapid spread of Group B resistance in brassica weeds and Group A and Z resistance in wild oat (*Avena* spp.) has significantly reduced the potential to apply this tactic.

Key benefit

- Correctly executed selective spray-topping will result in a 90% reduction in weed seed set in herbicide susceptible populations.

Key Practicality

- Know the herbicide resistance status of weeds before using selective spray-topping.

Crop-topping with non-selective herbicides

Crop-topping applies a non-selective herbicide (e.g. glyphosate or paraquat) before harvest when the target weed is at flowering or early grain fill. Crop-topping aims to minimise production of viable weed seed while also minimising yield loss. The selectivity of the crop-topping process is dependent on a sufficient gap in physiological maturity between crop and weed.

Currently, non-selective herbicide crop-topping registrations are limited to use in pulse crops and predominantly target annual ryegrass.

Key benefits

- Crop-topping can reduce annual ryegrass weed seed set, reducing additions to the seedbank.
- Reductions in seed set achieved by crop-topping can be increased if used in conjunction with selective herbicide treatments.

Key Practicalities

- The ideal time for crop-topping is when the annual ryegrass is just past flowering and the pulse crop is as mature as possible.
- Crop-topping should not be performed on crops where the grain is intended for use as seed or for sprouting.
- Crop-topping for wild radish and other brassica weed control in current pulse varieties is not recommended because of the closely matched rate of development of weed and crop.

Whole-farm benefits

Crop-topping can deliver a number of benefits in addition to reducing weed seed set, including:

- improved harvest due to even maturity of crops (particularly pulses)
- improved harvest, grain quality and storage by desiccating late weed growth in seasons with late rain.

Wiper technology

Wick wiping, blanket wiping, carpet wiping and rope wicking are all forms of weed wiping technology that aim to reduce weed seed set by using a range of devices to wipe low volumes of concentrated herbicide on to weeds that have emerged above the crop.

Key benefits

- Weed wiping is selective due to the application method rather than the herbicide used.
- Weed wiping is an effective method of reducing seed set in weeds which have not been controlled by tactics used earlier in the growing season.

Key Practicalities

- Care is needed to ensure that excess herbicide does not drip on to the crop and cause damage.
- Timing of weed wiping is the key.
- A special applicator is required for weed wiping.

Crop desiccation and windrowing

Crop desiccation and windrowing (also called swathing) are harvest aids which ignore the growth stage of any weeds present, so they are not true weed seed set control tactics. However, in certain conditions windrowing and crop desiccation can provide significant weed management benefits.

Windrowing canola on a farm near Old Junee, NSW.
Photo: Nicole Baxter

The tactics are defined as the termination of crop growth by physical (windrowing) or chemical (desiccation) means at physiological maturity or a later stage.

Key benefits

- Windrowing used in conjunction with other tactics can greatly enhance weed control results.
- There is a chance that crop desiccation or windrowing will reduce weed seed set.
- Windrowing or desiccation can help manage late germinating weeds.

Key practicalities

- Timing is the key to maximum yield and quality.
- Weed and crop regrowth (post-windrowing) must be controlled to stop seed set.
- Weeds and tillers below cutting height will not be incorporated into the windrow.
- Check herbicide labels.
- Windrowing in hot weather can increase losses due to shattering.

Whole-farm benefits

Windrowing and desiccation can:

- assist harvest schedule
- encourage even ripening of crops
- increase harvest speed and efficiency
- minimise yield loss from shattering or lodging
- enhance seed quality
- overcome harvest problems caused by late winter or early summer weed growth
- minimise weather damage during harvest by increasing the speed of drying, while protecting the crop in the windrow
- improve the yield of following crops by halting water use by the current crop. Crops can continue to use soil water when past physiological maturity.

Pasture spray-topping

The composition of a medium-term (‘phase’) pasture dominated by annual legumes and grasses (a three- to five-year pasture phase between crop phases in a rotation) changes over time. A pasture may be legume dominant in year 1 but often by year 3, without intervention, it will be dominated by annual weeds, often a result of low intensity set stocking. In some regions (and paddocks) the dominant annual weeds are broadleaf, but predominantly they are annual grasses.

Key benefits

- Strategically timed pasture spray-topping significantly reduces the production of viable weed seed in pastures.
- Both paraquat and glyphosate can be used for pasture spray-topping.
- Pasture spray-topping is a cost-effective tactic to reduce weed seed set and the weed seedbank.

Key Practicalities

- The timing of herbicide application is critical to the success of pasture spray-topping.
- Pasture spray-topping is not an alternative to fallow spraying.
- Pasture spray-topping as a lone tactic cannot control a wide range of grass species simultaneously.
- Grass weed levels determine the management ‘fit’ of pasture spray-topping in a pasture phase.
- Winter cleaning or fallow spraying may be a better option to finalise the pasture phase before cropping commences.
- Spray-topping can reduce seed set in annual pasture legumes if the legume pasture development stage coincides with the development stage of the target annual grass.

Whole-farm benefits

Additional benefits gained from pasture spray-topping include the following:

- The proportion of legume in the pasture is increased, resulting in improved feed value of the pasture and increased livestock production from grazing.
- Well-planned pasture spray-topping can be used to set up pastures for high-quality forage conservation (hay or silage) in the following spring.
- Pasture spray-topping is ideally used in the season before fallow initiation, reducing grass weeds and the risk of cereal disease carryover into the next winter crop.
- Pasture spray-topping can be effective against grass seed injuries to lambs' eyes and skin and damage to carcasses.

Silage and hay – crops and pastures

Silage and haymaking can be used to manage weeds by:

- reducing the quantity of viable seed set by target weeds
- removing viable weed seeds so that they are not added to the soil seedbank.

Key benefit

- Hay and silage are options that can be used in crops and pastures where excessive numbers of weeds have survived a previous tactic.

Key Practicalities

- Consider the balance of using hay or silage as a weed management tactic with other farm enterprises.
- Time the hay or silage tactic in accordance with the physiological development of the target weed.
- Carefully consider the options for marketing or using the product on-farm.
- Understand the biological traits of the target weed to improve efficacy of the tactic.
- Regrowth can produce enough seed to keep the seedbank topped up.

Manuring, mulching and hay freezing

Crops and pastures can be returned to the soil to reduce weed seedbanks, improve soil fertility and maintain soil organic matter. This can be done by burial, mulching or chemical desiccation.

Green manuring incorporates green plant residue into the soil with a cultivation implement. Most commonly conducted with an offset disc plough, cultivation aims to kill weeds and control seed set while building soil organic matter and nitrogen status. Green manuring has a very long history of managing weeds and building soil fertility in systems where herbicides are either not an option or not available, such as organic farming systems.

Brown manuring is simply a no-till version of green manuring, using a non-selective herbicide to desiccate the crop (and weeds) at flowering instead of using cultivation. The plant residues are left standing. This may also be a preferred option on lighter soils prone to erosion. Before spraying, the crop or pasture can be 'opened up' by grazing, followed by a recovery period, to enable better coverage with the herbicide. This might preclude the need for a double knock to control any regrowth. The standing residues can be grazed post-spraying after appropriate withholding periods have been observed.

Key benefits

- Manuring, mulching and/or hay freezing (all with regrowth control) reduce viable weed seed set, thereby controlling high weed numbers and managing herbicide resistant weeds.
- Costs (income loss) from the tactic can be offset by improved yield in subsequent cereal crops and/or by fattening trade stock.
- Weeds patches in crops can be treated before hectic harvest time.

Key Practicalities

- Manuring must be carefully timed to prevent seed set and addition to the seedbank.
- Choice of crop species will influence crop competitiveness.
- Economics in the year of manuring can be improved by planning for the tactic and by understanding and valuing subsequent benefits.
- Ensure good coverage and penetration of herbicide, and observe withholding periods when brown manuring or hay freezing.
- Maximise seed kill by ensuring even and optimum head emergence of target weed.
- Monitor and manage regrowth.

Whole-farm benefits

- Manuring allows continuous cropping to occur with lower production and financial risk.
- Manuring will have a beneficial effect on organic matter and soil nitrogen status. The benefit will be much greater if the crop or pasture being manured has a high legume content. Farm data from the NSW Riverina has shown early-sown pea brown manure crops giving 25 to 30% yield increases in the two subsequent crops.
- Manuring also allows fattening of trade stock before manuring takes place, therefore generating income.
- Green or brown manuring or hay freezing can be used to manage other crop pests and diseases. Using wild radish or other brassica weed species for manuring can also have beneficial soil fumigation effects for diseases.
- A competitive pulse manure crop followed by a canola crop gives an effective break to cereal root diseases and provides extended opportunities for grass weed control.
- Manuring a crop early can give sufficient time for the storage of soil moisture for the following crop.
- Hay freezing provides standing fodder for livestock.

Whole-farm considerations

There are multiple issues to consider when deciding when and how to use a manure crop or pasture:

- Cultivation leads to increased mineralisation of soil organic matter which needs to be considered when using green manuring. Brown manuring benefits soil organic matter.
- Lighter textured soils may have excessive structural damage under green manuring. Brown manuring helps retain soil structure and surface cover.
- The number of tillage passes required by green manuring for a successful kill may be affected by soil moisture, with more cultivations required in a wet spring.
- The feed value and quantity of hay freezing fodder depend on the plant species and dry matter content of the area treated. Generally, feed value drops rapidly and the treated area needs to be grazed within a few months of spraying to gain most benefit.
- The protein content and digestibility of fodder following hay freezing deteriorate rapidly after rain, and the fodder is lost to trampling over time. It does, however, provide and maintain better feed value than hayed-off standing pasture.
- A pasture hay-freezed at ryegrass flowering would be expected to maintain good quality for two months after spraying. After approximately three months the quality of the feed in the treated paddock will be similar to that in untreated paddocks (Arkell 1995).
- Plan to graze soon after treatment to avoid the risk of forage quality loss due to weather damage. Strip grazing with an electric or movable fence can reduce trampling loss.

Grazing – actively managing weeds in pastures

Pasture weed management requires maintaining a balance of pasture species (i.e. maximising the mix of desirable plants, legumes and specific grasses while keeping weed levels low).

Most weeds are susceptible to grazing. Weed management using grazing is achieved through reduction in seed set, competitive ability of the weed and the encouraged domination of desirable species. The impact is intensified when grazing coincides with the vulnerable stages of the weed life cycle.

In crop based rotations a two- to three-year pasture phase may significantly reduce weed seedbanks to manageable levels before returning to a cropping phase. During this period, pasture phase grazing in association with other tactics may be used to help reduce weed numbers. Grazing can be coupled with hay and silage making, mowing and pasture spray-topping for increased weed control.

Key benefits

- Timed grazing pressure can be used to manipulate pasture composition.
- Grazing can be used in conjunction with herbicides (spray-grazing) to effectively manage weeds.
- Grazing can be used to reduce seed set in grass weeds.
- Exploiting differences in species acceptability to sheep can reduce weed numbers.
- Tillering of annual grasses can be decreased by timely grazing.

Key Practicalities

- Grazing pressure needs to be high enough to prevent selective grazing.
- Timing of practices is critical to obtain the desired level of weed control.
- Manage grazing to avoid livestock importing weeds or transporting them to other paddocks.
- Livestock movement across paddocks can bury weed seeds.
- High grazing pressure can increase the proportion of broadleaf weeds such as capeweed and erodium.

Whole-farm benefits

Well-managed grazing provides other benefits on the farm:

- Grazing increases legume composition of pastures and improves feed quality.
- More productive legumes can improve levels of nitrogen fixation for the benefit of subsequent crops.
- Increased stocking rates under set stocking can increase wool production per hectare and reduce both the mean fleece fibre diameter and the variation in fibre diameter along the staple (Doyle et al 1993).

Whole-farm considerations

Determine the suitability of grazing as a weed management tactic by considering the following points:

- Livestock traffic can lead to soil compaction and erosion. Fine textured soils are more prone to compaction, especially if grazed after rain.
- Intensive grazing during the flowering and seed set stages of desirable species impedes their ability to set seed. The same paddock should not be intensively grazed in successive years (Doyle et al. 1993).
- Intensive spring grazing on some paddocks may lead to others being under-used. If there is excess feed, mow it for fodder or treat it with herbicides for weed control.

4. Stop adding to the seedbank

The most problematic weed species of annual cropping systems are prolific seed producers capable of establishing large, viable seedbanks in just one season. Despite this, the high proportion of seed retained on upright stems at crop maturity creates the potential to target these seeds at harvest. Thus weed seed control at harvest represents an excellent opportunity to control weed seeds, preventing their input to the seedbank.

Modern grain harvesters are efficient at sorting weed seed from crop grain, with the weed seeds returned to the field, primarily in the chaff fraction (Balsari et al 1994; Walsh and Powles 2007). For example, annual ryegrass (Lolium rigidum) and wild radish (Raphanus raphanistrum) can retain a large proportion of their seed attached to the plant at the same height as the crop seed-heads at crop maturity. Most of this seed can pass intact through the grain harvester returning to the crop field in the chaff fraction, thus perpetuating an ongoing weed problem (Walsh and Powles 2007). As most small weed seed exits with the chaff fraction, harvest weed seed control options target the harvest residue fraction. For example, up to 95% of annual ryegrass seed that enters the harvester will exit in the chaff fraction.

A recent scoping study in the northern grain region (Widderick and Walker 2012) has shown that there is potential to use harvest weed seed control techniques for some winter crops. In southern Queensland and northern New South Wales, field surveys at winter crop harvest showed sowthistle (*Sonchus oleraceus*) and possibly wild oats (*Avena* spp.) have the majority of their seeds above harvest height in chickpeas.

The weeds measured included fleabane (*Conyza* spp.) with 96% seed above harvest height, sowthistle with 78%, wild oat with 83%, turnip weed (*Rapistrum rugosum*), cudweed (*Gamochaeta* spp.) and paradoxa grass (*Phalaris paradoxa*) all with 100%, wireweed (*Polygonum* spp.) with 98% and black bindweed (*Fallopia convolvulus*) with 93%. In wheat crops, 66% of sowthistle and 96% of wild oat seeds were above harvest height but fleabane and turnip weed had much less seed above harvest height at 15 and 33% respectively.

Key benefits

- Weed seed control at harvest prevents a large proportion of viable weed seed entering the seedbank.
- Small crop grain is collected and removed in harvest residues.

Key Practicalities

- Cutting height should be as low as practically possible.
- Harvest timing affects the amount of seed collected during harvest.
- Farmers must have a strategy to dispose of collected harvest residues bearing weed seed.
- Repeated use and dependence on seed collection at harvest for weed control may favour the development of shorter, quicker maturing (early shedding) weed types.

Narrow header trail

The burning of crop residues is the oldest form of weed seed destruction to be used routinely in crop production systems. Stubble burning is typically conducted in autumn on crop fields to reduce stubble levels in preparation for seeding as well as for reducing the carryover of stubble-borne diseases. It is more common in the southern and western grain regions than in the northern region. The destruction of weed seeds has been a somewhat secondary but significant result of this practice.

During typical whole paddock stubble burning, very high temperatures (300 °C or greater) occur for only a few seconds. However, the effectiveness of weed seed destruction by burning is increased when seeds are exposed to these high temperatures over a period of several minutes. For example, to kill annual ryegrass seed requires temperatures of 400 °C for 10 seconds while 100% kill of wild radish seed retained in pod segments requires 500 °C for this same short 10 second duration (Walsh and Newman 2007). Higher burning temperatures (>500 °C) and longer durations (greater than three minutes) are only possible with high stubble levels. Therefore, when burning is used as a weed control option, concentrating harvest residues into a narrow windrow improves the weed control potential of this practice.

A header with a chute attached that is used to make narrow windrows for burning.
Photo: Peter Newman

Key benefits

- Narrow windrow burning effectively reduces viable weed seed numbers in the seedbank.
- Burning a narrow windrow reduces the percentage of the paddock that is burnt, thereby reducing the area prone to wind or water erosion.

Key Practicalities

- Best success will be achieved by a high temperature burn, accounting for seasonal risks.
- Burn windrows when there are light (5 to 10 kph) winds.
- Time burning to suit residue conditions and legislative limitations.
- Windrow burning is not suitable for barley stubble or high yielding wheat crop stubble.
- Windrows need to be moved each year to prevent concentration of potassium.

Chaff cart

Chaff carts are towed behind headers during harvest to collect the chaff fraction. Collected piles of chaff are then either burnt the following autumn or used as stock feed. Because of the considerable volume of chaff material produced during harvest, chaff heaps are typically burned the following autumn.

A chaff cart being used in Western Australia.
Photo: Evan Collis

Key benefits

- Collecting crop residue with a chaff cart can significantly reduce the numbers of weed seeds returning to the seedbank.
- Growers are using stock to graze chaff dumps reducing the need for supplementary feeding over summer and autumn

Key Practicalities

- Burning chaff heaps
- Grazing chaff heaps might spread weed seeds.
- Chaff dumps can smoulder for days, upsetting neighbours and town residents

Bale direct system

The bale direct system uses a baler attached to the harvester to collect all chaff and straw material. Approximately 95% of annual ryegrass seed entering the harvester is collected and removed in the baled material (Walsh and Powles 2007). As well as controlling weeds the baled material has an economic value as a livestock feed source.

Key benefit

- Direct baling of chaff and straw residues exiting the harvester is a highly effective harvest weed control tool.

Key Practicalities

- Set-up of bale direct system
- Sale of baled material

Chaff Mills – Harrington Seed Destructor and Seed Terminator

There are currently two types of impact mills on the market in Australia. The Harrington Seed Destructor (HSD) is the invention of Ray Harrington, a progressive farmer from Darkan, Western Australia. Initially developed as a trail-behind unit, the HSD system comprises a chaff processing cage mill and chaff and straw delivery systems. The current configuration is now integrated into new harvesters powered by a hydraulic drive system independent of the harvester and pulverises the entire chaff fraction.

The Seed Terminator developed in South Australia is another type of impact mill using the mechanical drive from the harvester to power the mill. HSD, chaff carts and narrow-windrow burning have similar effects on annual ryegrass seed collected during harvest (Walsh et al. 2017).

A Harrington Seed Destructor reducing ryegrass seed numbers in Western Australia.
Photo: Nicole Baxter

Key benefits

- Chaff mills control high proportions of weed seeds present in the chaff fraction at harvest.
- All harvest residues remain in the paddock.

Key Practicalities

- Cost - At the time of writing the HSD had a capital cost of approximately $160,000 while the Seed Terminator costs $115,000. The running costs, including depreciation, are approximately $17/ha (Kondinin Group, 2018)
- Selection for more prostrate or early shedding biotypes or species

Chaff lining and chaff decks

Chaff lining offers a low cost alternative for harvest weed seed management. The chute catches everything from off the sieves and concentrates weed seeds into a narrow row. Chaff decks concentrate the weed seeds onto the wheel tracks in a controlled traffic system. Constant traffic on the wheel tracks creates a less favourable environment for weeds to germinate (Kondinin Group 2018).

Key benefit

- Weed control can be targeted at a very small area

Key Practicalities

- Cost: Chaff deck prices range from $16,000 – $21,000 and can be fitted by the grower. The cost savings in herbicide application can be as much as $45/ha when only targeting the 'weedy' tramlines. (WeedSmart, Case Study. March 2018). The chaff chutes can be purchased off the shelf or home-made and adapted to individual harvesters. Kits range from $3500 to $5000, while grower-fabricated designs can be built for as little as $200.

Grazing crop residues

Grazing weed contaminated crop residue can be a cost-effective way of controlling weed growth. Animal digestion of weed seeds prevents a large proportion from entering the seedbank.

Note that the feed value of the crop residue will be variable, and grazing has the potential to spread undigested weed seeds.

Key benefits

- Grazing reduces the number of weed seeds added to the soil seedbank.
- Grazing can be used to dispose of, and gain value from, weed seed contaminated fodder.

Key Practicalities

- Grazing livestock can distribute weed seeds across a paddock.
- The impact of grazing on weed numbers entering the seedbank is dependent on the biological features of the weed.
- Livestock trampling tends to bury weed seed, which can decrease the efficiency of burning as a means of killing seeds. Depending on the weed species, burial may also increase germination rates.

Whole-farm benefits

There are additional benefits when using grazing of crop residue as a weed management tactic:

- Weed seeds can provide a significant proportion of the nutritional value when stock graze crop residue.
- Post-harvest grazing may reduce crop establishment problems by reducing stubble burdens.
- Seed burial through trampling may enhance weed germination pre-sowing. Using a knockdown herbicide and delaying sowing can then capitalise on this process.
- Seed of desirable plants (pasture species) may be distributed in faeces.

Whole-farm considerations

Grazing may also cause:

- an increased risk of soil, water and wind erosion
- increased soil compaction
- potential toxicity issues for sheep, e.g. lupinosis.

5. On farm hygiene

'Risk aware' growers can implement strategies to reduce and avoid unnecessary introduction and spread of weeds. These strategies will reduce not only the likelihood of introducing new weed species but also the risk of importing herbicide resistant weeds.

Key benefits

- Planning and enforcing a farm hygiene strategy minimises the risk of adding weeds to the seedbank from external sources.
- Weed seeds will not be added to the seedbank from other areas of the same paddock, other paddocks on the same farm, other farms or other regions.
- Management costs will be reduced in the long term.
- Weed problems will be quarantined or confined to known areas where they can be more effectively managed.
- The risk of introducing herbicide resistant weed populations from alternative sources into paddocks and on to the farm will be reduced.

Sow weed-free seed

Key benefits

- Weed seeds are not added to the seedbank unnecessarily.

Key Practicalities

- Check seed analysis before purchasing seed-lots to avoid importing weed seed.
- Plan ahead when retaining seed on-farm for sowing.
- Keep good records of seed purchases.

Manage weeds in non-crop areas

Key benefit

- Weed management in non-crop areas can prevent 'creep effect' into crops.

Key Practicality

- Weeds in non-crop areas can impact greatly on farm weed status, but are often easily controlled.

Clean farm machinery and vehicles

Key benefit

- Good vehicle hygiene (i.e. regular cleaning) can reduce the risk of new infestations and weed spread

Key Practicality

- Develop and adhere to a clean machinery and vehicle protocol aimed at reducing new additions to the weed seedbank.

Manage livestock feeding and movement

Key benefits

- Careful management of livestock will reduce the likelihood of new infestations and weed spread.

Key Practicalities

- Quarantine contaminated fodder in a sacrifice paddock or feedlot so that weeds are contained in a small area.

Monitor paddocks following flood for new weed incursions

Key benefits

- Low level infestations of new weeds can be controlled at low cost and most likely eradicated.

Key Practicalities

- Good observation for what weeds are new or different is needed to identify potential new threats.

NOTES

ADDITIONAL RESOURCES

Australian herbicide resistance initiative (AHRI) – Understanding herbicide resistance, weeds, and their management
https://ahri.uwa.edu.au/

Weedsmart – weed management case studies, webinars, factsheets and podcasts
https://weedsmart.org.au/

GRDC Integrated weed management hub – Weeds resources including the Integrated Weed Management manual and factsheets
https://grdc.com.au/IWMM

Free short courses on herbicide resistance, harvest weed seed control and pre-emergent herbicides.
https://www.diversityera.com/

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