HERBICIDE USE

CLASSIFICATION
MODES OF ACTION BY HERBICIDE
HERBICIDE RESISTANCE
APPLICATION
HEALTH AND ENVIRONMENTAL EFFECTS

LABELLING AND TRAINING
GRDC PROJECTS
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6.1 Labelling of chemicals

6.2 Reading a chemical label

6.2.1 SECTION A: warnings and product description

A.1 The Signal Heading

A.2 Brand Name (or Trade Name)

A.3 Type of Chemical

A.4 Active Constituent

A.5 Resistance Group

A.6 What the Chemical Does

A.7 Name, address and phone number of the business that made the chemical

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6.3 Maximum residue limits (MRLs) and Withholding periods (WHP)

6.4 Record keeping

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Classification

1.1 Activity

Herbicides can be broadly divided into selective and non-selective herbicides, meaning that some only kill certain types of plants such as grasses, whereas others are broad spectrum and kill all plants they contact. They can also be grouped by their mode of action (MOA).

Contact herbicides kill plant tissue on contact and are often quick acting. They have limited movement in the plant and usually have no soil activity. Selectivity is limited but they can be used to control small annual weeds in well-established annual or perennial pastures or crops.

Translocated herbicides are taken up by one part of the plant and moved to other parts; some are more active via the foliage whereas others are more active via the roots.

Soil-active herbicides act on seeds or roots and/or shoots of germinating weeds, or roots of established weeds.

Soil-residual herbicides are soil-active herbicides which remain active over a period of time. The length of the residual action depends mainly on the nature of the chemical itself, the rates applied, the climate, the properties of the soil, e.g. high or low in clay or organic matter, and the rate of uptake by the weeds. Residual activity is particularly important when considering subsequent crops and pastures.

1.2 Timing of application

In cropping and pasture situations the herbicide applications are related to time of germination and subsequent emergence of the sown crop or pasture, and the germination and emergence of weeds.

1. Pre-plant: The herbicide is used either as a knockdown or short-residual herbicide to control weeds before planting. This is applicable to minimum tillage, direct drilling or fallow spraying.

2. Pre-plant soil-incorporated: Herbicides in this class are usually soil active and require incorporation into soil shortly after application to prevent loss by volatility or photolysis and to place the herbicide in the soil where weed seeds will germinate.

3. Pre-emergence crop, pasture and weeds: Where the herbicide is applied prior to or shortly after planting to kill or control germinating weeds, but allow the crop or pasture to germinate and grow through the treated soil.

4. Pre-emergence crop or pasture post-emergence weeds: Where the safest treatment is to use a quick-acting contact herbicide to kill or control the weeds before the crop emerges. Nevertheless, translocated or soil-active residual herbicides may be applied instead of or with the contact herbicide so long as selectivity towards the crop is certain.

5. Post-emergence crop or pasture and pre-emergence weeds: Where selective soil-active herbicides may be sprayed over the crop to control germinating weeds.

6. Post-emergence crop, pasture and weeds: Where certain selective contact and translocated herbicides may be used to kill or control the weeds without significant harm to crop or pasture. The stage of growth of both the crop or pasture and weeds is often critical in determining whether the treatment is successful.
1.3 Method of application

Herbicides can be applied by a variety of methods. The aim of a successful spray application is to ensure the correct amount of chemical is applied to the intended target with no contamination of off-target areas. The herbicide label will specify the application methods suitable to its registered uses and give recommendations for minimising spray drift.

![Photo 1](Image)

Growers are urged to consult herbicide labels which specify suitable application methods for registered uses.

Source: GRDC

1.3.1 Boom sprayer

A boom sprayer is the most common type of apparatus for applying herbicides in broadscale farming. A sprayer has many components, the most important being the nozzles, which split the herbicide into many small droplets that are projected through the air to the target. The nozzle is the only component of the sprayer that directly determines the effectiveness of spraying. All other components are necessary to position the nozzles and provide them with a continuous supply of herbicide at the correct pressure. Correct nozzle selection and operation are critical for successful spraying.

1.3.2 Misters

Misters are a useful but imprecise way of applying herbicides to large areas quickly. They rely on wind to drift the herbicide. If the wind is too light or the spraying speed too high, the swath width will decrease, possibly causing overdosing and wasted chemical. If the wind is too strong or gusty, it increases the swath width, which will reduce the chemical application rate and increase the risk of damage from spray drift.

1.3.3 Blanket wipers and rope wick applicators

Blanket wipers are made of a vertical strip of material attached to a horizontal frame. The vertical strip, or blanket, acts as the wiping surface making direct contact with the target weed. This equipment has been developed as an alternative to rope wick applicators. A non-selective herbicide is generally used with successful weed control dependant on the height differential between crop and weed. Wipers are used in broadacre application to control radish or mustard in lupins or chickpeas or to ‘top’ grasses in pasture. The best time to wipe weeds in crops is September to early
October when the weeds are flowering and are 20–30 centimetre taller than crop or pasture plants.

Rope wick applicators consist of a series of ropes impregnated with a non-selective herbicide, usually glyphosate. They are not widely used, but they can be useful for the control of tall weeds in a crop or pasture. Normal spraying with a non-selective herbicide would not be possible in this situation, however a rope wick applicator can be moved above the crop or pasture and wipe the herbicide only onto the taller weeds, hence selective control is obtained. Because they can only operate at slow speeds and the ropes are very expensive, rope wick applicators have not gained wide acceptance.

1.3.4 Detection technology

Detection technology (for example, Weedseeker® and WeedIt®) uses infrared and near infrared light to detect green weeds and sprays only green plants in paddocks. In action, light-emitting diodes (LEDs) point two different light sources, infrared and near infrared, towards the ground. Green weeds have a different reflective signature to stubble or soil. The system can operate at speeds up to 20 kilometres per hour (km/h), requiring a stable boom to aid operational efficiency.

Photo 2: Detection technology is reducing the amount of herbicides used. Source: Crop Optics.

1.3.5 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.

Vigilance and attention to detail can be the difference between eradication and a prolonged and costly problem. Make sure you correctly identify the weed, understand the biology (when does it grow, when does it reproduce etcetera) and identify what control tactics are best suited to the weed at each growth stage.

To ensure the eradication program is successful:

- instigate accurate future monitoring by marking isolated infestations
- isolate the area of infestation to reduce the risk of further spread.
- Techniques for localised eradication
**Section 1: Herbicide Use**

**1.3.6 Roguing**

Roguing refers to hand pulling or chipping of weeds prior to flowering or seed-set. It is also used in seed crops to reduce the chance of spreading weeds in the seed and when other options of controlling the weed are limited. If roguing is carried out after seed is physiologically mature, both the plants and their seeds should be contained and carefully disposed of. Roguing is an effective method of eradicating a small infestation in annual crops, despite being labour intensive and expensive.

**1.3.7 Spot spraying**

This method is a quicker alternative to hand roguing and can be used to kill the plant or sterilise weed seed. Spot spraying usually involves the application of a non-selective herbicide to individual weeds using a sprayer in a backpack or mounted on an all terrain vehicle (ATV). The sprayer should have a single nozzle on a wand attached to a flexible hose. A boom sprayer fitted with weed detector units may also be used for applying non-selective herbicides to low-density infestations in fallows.

**1.3.8 Wick wiping**

Wick wiping performed with a hand-held rope-wick wiper is an alternative to spot spraying when there is the possibility of herbicide drift onto sensitive adjacent plants. It is particularly useful if the weed is taller than the crop canopy. There are multiple ‘wiper technologies’ available, including wick wipers, rope wipers, carpet wipers and weed wipers.

**1.4 Chemical family**

**1.4.1 Classification**

It is important to recognise the MOA group for each herbicide so that herbicide resistance can be managed. However, it is also important to understand how herbicides work so that the grower gets the best weed control results. In Section 2 the MOA groups are described and the important features of each group are related to the recommended label instructions. These include uptake and translocation in the weed, crop selectivity, spray application and environmental conditions.

Australian law requires all agricultural and veterinary chemical products sold in Australia to be registered by the Australian Pesticides and Veterinary Medicines Authority (APVMA).

Once a product is registered, it is approved for the purposes and uses stated on the product’s label. Situations often arise where chemicals are needed for a use not specified on the label, these are often termed ‘off-label’ uses. The APVMA considers applications for permits that allow for the legal use of chemicals in ways different from those set out on the product label. In certain circumstances, the limited use of an unregistered chemical may also be allowed by permit.

APVMA is the regulatory authority that approves active constituents and registered Agricultural Chemicals. Each state and territory has Control of Use legislation that regulates the use of these chemicals. This legislation varies from state to state. Most states have a requirement to undertake training before using certain chemicals.

The relevant training courses can be found via AusChem and ChemCert.

An over-arching national classification system also controls how chemicals are made available to the public. Chemicals are classified into schedules according to the level of regulatory control (over the availability of the chemical) that is needed to protect public health and safety. These schedules accompany states’ and territories’ Poisons Acts and list the various poisons under categories.
Herbicide Group A modes of action

Herbicide resistance is caused by the intensive use of herbicides for weed control. A small number of weeds can be naturally resistant to herbicides, even before the herbicides are used. When a herbicide is used, these individual weeds can survive and set seed, whereas the majority of susceptible plants are killed. Continued use of a herbicide or herbicide group will eventually result in a significant number of the weed population developing resistance.

One of the most important methods for preventing, delaying, or managing resistance is to reduce the reliance on a single herbicide MOA. To do this, growers must be aware of the MOA for the herbicides they intend to use, but the relatively complex nature of plant biochemistry makes this difficult to determine. Therefore, a classification system for herbicides based on their mode of action to the herbicide has been developed.

The Group A Mode of Action (MoA) herbicides are also called ACCase (acetyl co-enzyme A carboxylase) inhibitors. They are classified as Group A by the global Herbicide Resistance Action Committee (HRAC) and Group 1 by the Weed Science Society of America (WSSA) (http://hrac.tsstaging.com/tools/classification-lookup).

There are three chemical classes within the Group A MoA as shown in Table 1. These classes are different types of chemicals; however, they affect the same biochemical pathways in the plant.

The MOA table and the herbicide resistance management strategies with their specific guidelines can be found on the CropLife Australia website www.croplifeaustralia.org.au.

To facilitate management of herbicide resistant weeds, all herbicides sold in Australia are grouped by MOA which is indicated by a letter code on the product label. It is displayed on the front panel of the label in a box as such:

<table>
<thead>
<tr>
<th>Group</th>
<th>Herbicide</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td></td>
</tr>
</tbody>
</table>

Group A herbicides are primarily active on grasses (monocots) and a limited number of broadleaf (dicot) weeds. This selectivity occurs because Group A herbicides cannot bind to the ACCase enzymes of most broadleaf plants.
Table 1: Herbicides included in Group A.

<table>
<thead>
<tr>
<th>Chemical class</th>
<th>Active ingredient</th>
<th>Product examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aryloxyphenoxypropionates 'fops'</td>
<td>Clodinafop</td>
<td>Topik®</td>
</tr>
<tr>
<td></td>
<td>Cyhalofop</td>
<td>Barnstorm®</td>
</tr>
<tr>
<td></td>
<td>Diclofop</td>
<td>Halley Diclofop Herbicide, Cheetah® Gold</td>
</tr>
<tr>
<td></td>
<td>Fluazifop</td>
<td>Fusilade®</td>
</tr>
<tr>
<td></td>
<td>Haloxyfop</td>
<td>Verdict®</td>
</tr>
<tr>
<td></td>
<td>Propaquizafop</td>
<td>Shogun®</td>
</tr>
<tr>
<td></td>
<td>Quizalofop</td>
<td>Targa®</td>
</tr>
<tr>
<td>Cyclohexanediones 'dims'</td>
<td>Butroxydim</td>
<td>Factor®</td>
</tr>
<tr>
<td></td>
<td>Clethodim</td>
<td>Select®</td>
</tr>
<tr>
<td></td>
<td>Profoxydim</td>
<td>Aura®</td>
</tr>
<tr>
<td></td>
<td>Sethoxydim</td>
<td>Sertin®, Cheetah® Gold, Decision®</td>
</tr>
<tr>
<td></td>
<td>Tralkoxydim</td>
<td>Achieve®</td>
</tr>
<tr>
<td>Phenylpyrazoles 'dens'</td>
<td>Pinoxaden</td>
<td>Axial®</td>
</tr>
</tbody>
</table>

Cheetah® Gold, Decision® and Axial® contain more than one active constituent.

2A.1 Mode of action and biochemical pathways

Group A herbicides block ACCase, the first enzyme in the production of fatty acids. This process primarily occurs in the chloroplasts. Stearic acid (16 carbon atoms) and palmitic acid (18 carbon atoms) are produced and released to the cell fluid (cytoplasm) and are essential components of cell and chloroplast membranes.

These fatty acids are also used as building blocks for suberin, cutin and waxes. Suberin is a long-chain waxy material found in plant cell walls, the endodermis (the Casparian strip), and the cuticle. Cutin is a waxy, transparent material in the cuticle of plants that contains highly polymerised esters of fatty acids.

Blocking ACCase halts the manufacture of cell membranes, which is necessary for cell growth.

Most of this activity occurs in the meristem in the base of actively growing leaves and the crown region of the plant. Group A herbicides slow and stop growth in these regions leading to senescence and eventually tiller death.

For a detailed explanation go to: Plant & Soil Sciences eLibrary Lessons: Inhibitors of fatty acid synthesis and elongation.
2A.2 Absorption into the plant

Group A herbicides are absorbed primarily via the leaves; however, diclofop and dimis are also absorbed through the roots under certain conditions.

Group A herbicides are lipophilic, penetrating the cuticle and entering the leaves quickly. Because most Group A herbicides have very low solubility in water (Table 2), they are formulated as emulsifiable concentrates in an organic solvent so they will mix with water.
Fops are also formulated as ‘pro-herbicides’ by adding a methyl, ethyl or butyl ester group to the acid form. This assists absorption through the cuticle. Like Group I herbicides, fops are converted to the active form (acid) once inside the plant.

Dims and dens do not need to be formulated as pro-herbicides to enter the plant.

### Table 2: Environmental characteristics of Group A herbicides.

<table>
<thead>
<tr>
<th>Group A class</th>
<th>Active ingredient</th>
<th>Example trade name</th>
<th>Water solubility (mg/L)</th>
<th>Log Kow</th>
<th>Persistence in soil (half-life @ 20°C) (days)</th>
<th>Soil mobility (Koc/Kfoc)</th>
<th>Breakdown by light under moist conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aryloxyphenoxypropionates (fops)</td>
<td>Diclofop-methyl ester</td>
<td>Halley Diclofop Herbicide</td>
<td>0.4</td>
<td>4.8</td>
<td>10–30 (acid)</td>
<td>20,870, non-mobile</td>
<td>Slow</td>
</tr>
<tr>
<td></td>
<td>Clodinafop-propargyl</td>
<td>Topik®</td>
<td>4 (acid)</td>
<td>3.9</td>
<td>5–20 (acid)</td>
<td>1466, slightly mobile</td>
<td>Fast</td>
</tr>
<tr>
<td></td>
<td>Haloxyfop-p-methyl</td>
<td>Verdict®</td>
<td>7.9</td>
<td>4</td>
<td>55</td>
<td>Rapid degradation, no data</td>
<td>Slow</td>
</tr>
<tr>
<td></td>
<td>Quizalofop-ethyl</td>
<td>Targa®</td>
<td>0.61</td>
<td>4.61</td>
<td>1.8</td>
<td>540, slightly mobile</td>
<td>Stable</td>
</tr>
<tr>
<td>Cyclohexanediones (dims)</td>
<td>Clethodim</td>
<td>Select®</td>
<td>&gt;3000 (pH 5)</td>
<td>4.14</td>
<td>28 (pH 5) 300 (pH 7)</td>
<td>22.7, mobile</td>
<td>Fast</td>
</tr>
<tr>
<td></td>
<td>Sethoxydim</td>
<td>Sertin®</td>
<td>4700</td>
<td>1.65</td>
<td>5</td>
<td>75, moderately mobile</td>
<td>Fast</td>
</tr>
<tr>
<td></td>
<td>Tralkoxydim</td>
<td>Achieve®</td>
<td>6.1</td>
<td>2.1</td>
<td>2</td>
<td>120, mobile</td>
<td>Moderate</td>
</tr>
<tr>
<td>Phenylpyrazoles (dens)</td>
<td>Pinoxaden</td>
<td>Axial®</td>
<td>200</td>
<td>0.6</td>
<td>349, moderately mobile</td>
<td>Slow</td>
<td></td>
</tr>
</tbody>
</table>

Log \(K_{oc}\), ratio of herbicide that is soluble in octanol (organic solvent) v. water; it is a good indicator of the lipophilic or hydrophilic nature of a herbicide; larger the log \(K_{oc}\), value the more lipophilic the herbicide; herbicides with values between −1 and 1 should move in the phloem following foliar application. \(K_{oc}/K_{foc}\) >1000, binds strongly to soil; <500, moves in water. Solubility will vary with temperature and to a lesser degree pH.


### 2A.3 Translocation within the plant

Group A herbicides are weak acids. Weak acids are compounds containing a functional group, usually a carboxylic acid. This functional group gains or loses a hydrogen ion (H+) depending on the pH of the surrounding solution.

The plant cell cytoplasm has a higher pH (~7.5) than the outside of the cell because the cell membrane pumps H+ ions through the cell wall. Weak acid herbicides are more fat-soluble (lipophilic) when outside the cell, owing to the lower pH. This helps weak acid herbicides to move through the cell membrane. Once inside the cell, the herbicide molecule becomes ionised (i.e. it loses an H+) and is trapped in the cell as it becomes more water-soluble and cannot pass back through the cell membrane.

Although fops and some dims are weak acid herbicides, movement within the plant is slow and limited because of their low water solubility. Fop movement through the plant is primarily via the phloem (symplast); however, dims move via both phloem and xylem (apoplasm) (see box text for definitions).

They rapidly diffuse across the cell membrane (plasmalemma) but then they become trapped within the phloem cells.
Symplastic movement (the symplast is the network of all parts of the plant that have a membrane, including the phloem):

- Movement of water and solutes through the continuous connection of cytoplasm (via plasmodesmata).
- No crossing of the plasma membrane once it is in the symplast; however, if the solute was initially external to the cell, then it must have crossed one plasma membrane to enter the symplast.

Apoplastic movement (the apoplast is the space outside the plasma membrane, including cell walls and intercellular material):

- Movement of water and solutes through the cell walls and the intercellular spaces.
- No crossing of the plasma membrane.
- More rapid; less resistance to the flow of water.
- The xylem is part of this system because it is composed primarily of non-living cells (tracheids and xylem vessels).

2A.4 Symptoms

Growth ceases quickly following foliar application on small plants and more slowly on tillered plants. New leaf sheaths turn yellow and eventually brown. Shoot meristems die, and can best be observed by gently tugging the newest leaf, which should pull out and be yellow to brown.

Photo 2: Group A symptoms, new leaf pulls out easily from the crown

Photo: author unknown, GRDC Herbicide Damage Ute Guide
Photo 3: Ryegrass showing Clethodim damage
Photo: Chris Preston

Photo 4: Axial banding in wheat
Photo: Trevor Kien, Syngenta
Leaves turn bluey green, with older, fully formed leaves turning orange to red followed by general plant death. Older, well-tillered plants can often look unaffected until the youngest leaf in a tiller is gently pulled out to reveal the dead meristematic area at the leaf base.

2A.4.1 Timeframe for symptoms and plant death

Rate of development of symptoms and subsequent damage and death depend on plant species, herbicide dose, age and size of plant, and rate of plant growth. Death occurs from as early as two weeks to around four–six weeks post-application.

2A.5 Crop selectivity

Most dicots have an ACCase enzyme that does not allow the binding of Group A herbicides. The exception is Erodium spp., which are sensitive to haloxyfop. Limited research has also demonstrated that many species from the family Geraniaceae are sensitive to haloxyfop.

There is variation with respect to which species are controlled by different Group A herbicides. Group A herbicides do not control winter grass (Poa annua) or silver grass (Vulpia spp.). Generally, fops have more activity on volunteer cereals, annual ryegrass, barley grass, brome grass and wild oats. Dims, on the other hand, have more activity on summer grasses.

Cereal crops are tolerant of a range of Group A herbicides (Table 3), and there is rapid metabolism of the herbicide to nontoxic compounds. Often a ‘safener’ such as mefenpyr-diethyl is combined with the herbicide; safeners boost the levels...
of cytochrome P450, increasing the herbicide metabolism within the crop plant. Research has shown that the level of cytochrome boosting by safeners varies between wheat cultivars. A similar effect has been found in some fop herbicides by adding MCPA or a sulfonylurea (Group B) herbicide to the tank mix.

Several Group A herbicides are also toxic to cereal crops because they are not metabolised by P450 enzymes (see Table 3).

The breakdown compounds of sethoxydim are also phytotoxic, so they too have herbicidal activity. Breakdown products of most Group A herbicides are not phytotoxic.

### Table 3: Differences in selectivity between Group A chemical classes.

<table>
<thead>
<tr>
<th>Herbicide</th>
<th>Selective in some small-grain cereals</th>
<th>Non-selective in small-grain cereals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fops</td>
<td>Clodinafop-propargyl</td>
<td>Fluazifop-p</td>
</tr>
<tr>
<td></td>
<td>Cyhalofop-butyl (rice)</td>
<td>Haloxyfop-r</td>
</tr>
<tr>
<td></td>
<td>Diclofop-methyl</td>
<td>Propaquizafop</td>
</tr>
<tr>
<td>Dims</td>
<td>Profoxydim (rice)</td>
<td>Butroxydim</td>
</tr>
<tr>
<td></td>
<td>Traikoxydim</td>
<td>Ciethodim</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sethoxydim</td>
</tr>
<tr>
<td>Dens</td>
<td>Pinoxaden</td>
<td></td>
</tr>
</tbody>
</table>

### 2A.6 Soil activity

Although rarely noted on product labels, it has been known since the commercial release in the late 1970s of Group A herbicides that they have soil activity under certain conditions. Group A herbicides applied to bare dry soil a short time before sowing have been found to kill emerging cereal crops.

The level of soil activity is mediated by:

- herbicide type—significant differences between Group A herbicides
- herbicide rate—the higher the rate the better the control
- soil texture and pH—soils with lower proportion of clay will have more herbicide activity
- weed-crop density—interception of herbicide affecting soil activity
- photodecomposition—amount of light breaking down herbicide
- microbial breakdown—amount of soil moisture for microbes
- low water solubility—will keep herbicide near the surface.

Glasshouse experiments investigating the soil activity of foliar-applied fluazifop at two rates on barnyard grass (*Echinochloa crus-galli*) and at two densities (three and 50 plants per pot) found that herbicide interception with vermiculite (on the surface of the potting soil) reduced control by 51–18% at three plants per pot and by 22–19% at 50 plants per pot. The level of control was influenced by herbicide rate at both weed densities in the vermiculite treatments. Herbicide rate had less effect at the higher weed density, with more herbicide being intercepted and giving lower control at both herbicide rates.

Soil-absorbed diclofop and dms prevent growth of the primary root, and leaves fail to emerge from the coleoptile. Larger plants will have some inhibition of root growth.
2A.7 Effect of environmental conditions on activity

Group A herbicides are oil-soluble (lipophilic), so are rapidly absorbed by the leaf cuticle. However, owing to their low solubility in water, the rate of translocation within the phloem is slow.

2A.7.1 Light

High light conditions can thicken the cuticle of a weed, which will absorb a large proportion of the lipophilic herbicide. Dim herbicides are rapidly decomposed by ultraviolet light and are decomposed within a few days.

A decrease in light intensity, such as in autumn, increases the ratio between shoots and rhizomes in perennial species, which leads to better control through better herbicide interception and to more herbicide translocating to the root system. There is also an increase in the amount of assimilates moving into roots and storage organs, which in turn increases the transport of phloem mobile Group A herbicides.

2A.7.2 Temperature

As temperature increases, the rate of uptake of herbicide increases provided respiration and photosynthesis are not limited by the conditions. However, the total amount of herbicide absorbed by the plant does not change. High temperatures and low available soil moisture reduce herbicide translocation through the shutdown of transpiration.

Optimum temperatures for photosynthesis and respiration are determined by whether the plants use C3 or C4 photosynthesis. C3 plants grow best at temperatures <30°C, whereas C4 plants can actively grow at temperatures up to 35°C and at higher light intensities.

Frost can shut down plant growth for several days, leading to increased crop damage. The Achieve® label specifies not to apply to weeds or crops under stress due to severe frost. Increased crop damage results from lower production of P450 enzymes due to reduced crop growth, so that the herbicide is deactivated more slowly within the crop plant.

Analysis of 59 experiments investigating the efficacy of clodinafop-propargyl on wild oats (Avena spp.) showed that the level of weed control was strongly influenced by:

- the sum of the minimum temperatures for the seven days before spraying
- maximum temperature on the day of spraying.

The analysis found that the effect of low temperature stress on efficacy could be lessened by increasing the herbicide rate and application volume. Increasing the application volume should also improve spray coverage.

2A.7.3 Humidity

The main effect of humidity with Group A herbicides is the likelihood that weeds will be actively growing and will translocate the herbicide to the meristems. This assumes adequate soil moisture. High humidity and low soil moisture will slow transpiration and therefore photosynthesis and growth reducing levels of control.

2A.7.4 Soil moisture stress

Stressed plants have thicker cuticles that will absorb and retain more Group A herbicides. Moisture stress will reduce translocation of the herbicide and reduce herbicide efficacy. Addition of certain adjuvants can assist herbicide absorption into the plant, however, if it is not actively growing, translocation and efficacy will be limited. Analysis of clodinafop efficacy trials mentioned above also showed that by increasing herbicide rate and application volume (i.e. spray coverage), soil moisture stress could be partially overcome.
Sufficient soil moisture is also required for the rapid microbial breakdown of these herbicides.

2A.7.5 Rainfall

Group A herbicides can be rain-fast anywhere between 30 minutes and several hours. This is also likely to vary with weed species, depending on the amount epicuticular wax present on the leaf.

Dew or light rain soon after application has been known to increase crop damage because herbicide runs into the leaf axils, increasing the quantity absorbed. This can overwhelm the enzymes responsible for metabolising the herbicide before it reaches the meristem, leading to crop damage.

2A.8 Spray application

Because of the slow translocation of Group A herbicides within the plant, good spray coverage is essential.

Label recommendations vary from specifying a minimum application volume of 50 litres per hectare to specifying that no less than 50% of the droplets are in the range 150–300 microns. Others specify 110° nozzles and warn about the use of air induction nozzles, hollow cones and flood jets.

The Factor® label recommends medium to coarse spray quality and addition of oil adjuvant.

Other labels suggest a fine–medium spray quality. All suggest increasing application volume with dense crops and weeds.

Recent research has shown that using a medium spray quality at 60–80 litres per hectare gives excellent coverage. Medium spray quality will also have better penetration of crop and weed canopies than fine spray quality. Use of fine spray quality without air-assist is likely to lead to the off-target loss of 50% of the spray.

2A.8.1 Adjuvants

All Group A herbicides require an adjuvant to improve their deposition and uptake. Most commonly, the preferred adjuvant is crop oil. Often if tank-mixing with a herbicide for broadleaf weeds, a non-ionic surfactant is recommended in place of crop oil to lessen potential crop damage.

Read the label for recommended use of adjuvants.

2A.8.2 Water quality

Temperature

No data are available on the effect of low spray solution temperatures on efficacy.

pH

The effect of the pH of a spray solution is one of the most widely misunderstood concepts in spray application. The pH will have little effect on efficacy. Dropping the pH of a spray solution with an unbuffered product can lead to herbicide coming out of solution. Do not leave spray premixed overnight.

The water pH can affect a product’s half life in the spray tank.

Hardness

Group A herbicides are weak acids and as such can be affected by hard water. Dim herbicides are particularly sensitive to bicarbonate ions and concentrations as low as 250 ppm can severely impact on herbicide effectiveness.
If using bore water, or in an area with a lot of limestone, water should be specifically tested for bicarbonate. Bicarbonate will not be detected by normal hardness tests or hardness test strips.

Hardness can be largely counteracted by the use of ammonium sulfate dissolved in the spray water before the herbicide is added.

**Turbidity**

Muddy water with low levels of algae pose a risk of filter and nozzle blockage.

**2A.9 Further reading**


Herbicide Group B modes of action

The Group B Mode of Action (MoA) herbicides are also called ALS (acetolactate synthase) inhibitors. They are also classified as Group B by the global Herbicide Resistance Action Committee (HRAC) and Group 2 by the Weed Science Society of America (WSSA) (http://hrac.tsstaging.com/tools/classification-lookup).

There are four chemical classes within the Group B MoA as shown in Table 1. These classes are different types of chemicals; however, they affect the same biochemical pathways in the plant.

Group B herbicides can be active on both grasses and broadleaf (dicot) weeds. They can be used for pre- and post-emergent weed control on a range of crops and pastures. Some are used in fallows and some for total vegetation control.

<table>
<thead>
<tr>
<th>Chemical class</th>
<th>Active ingredient</th>
<th>Product examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imidazolinones 'imis'</td>
<td>Imazamox</td>
<td>Intervix® (PM), Raptor®</td>
</tr>
<tr>
<td></td>
<td>Imazapic</td>
<td>Flame®, Midas® (PM), OnDuty® (PM)</td>
</tr>
<tr>
<td></td>
<td>Imazapyr</td>
<td>Arsenal® Xpress, Intervix® (PM), Lightning® (PM), Midas® (PM), OnDuty® (PM)</td>
</tr>
<tr>
<td></td>
<td>Imazethapyr</td>
<td>Spinnaker®, Lightning® (PM)</td>
</tr>
<tr>
<td>Pyrimidinylthiobenzoates 'benzoates'</td>
<td>Bispyribac</td>
<td>Nominee®</td>
</tr>
<tr>
<td>Sulfonyleureas 'SUs'</td>
<td>Azimsulfuron</td>
<td>Gulliver®</td>
</tr>
<tr>
<td></td>
<td>Bensulfuron</td>
<td>Londax®</td>
</tr>
<tr>
<td></td>
<td>Chlorsulfuron</td>
<td>Lusta®</td>
</tr>
<tr>
<td></td>
<td>Ethoxysulfuron</td>
<td>Hero®</td>
</tr>
<tr>
<td></td>
<td>Foramsulfuron</td>
<td>Tribute®</td>
</tr>
<tr>
<td></td>
<td>Halosulfuron</td>
<td>Sempra®</td>
</tr>
<tr>
<td></td>
<td>Iodosulfuron</td>
<td>Hussar® (CS)</td>
</tr>
<tr>
<td></td>
<td>Mesosulfuron</td>
<td>Atlantis® (CS)</td>
</tr>
<tr>
<td></td>
<td>Metsulfuron</td>
<td>Ally®, Stinger® (PM), Trounce® (PM)</td>
</tr>
<tr>
<td></td>
<td>Prosulfuron</td>
<td>Casper® (PM)</td>
</tr>
<tr>
<td></td>
<td>Rimsulfuron</td>
<td>Titus®</td>
</tr>
<tr>
<td></td>
<td>Sulfometuron</td>
<td>Oust®</td>
</tr>
<tr>
<td></td>
<td>Sulfosulfuron</td>
<td>Monza®</td>
</tr>
<tr>
<td></td>
<td>Thifensulfuron</td>
<td>Harass®</td>
</tr>
<tr>
<td></td>
<td>Triasulfuron</td>
<td>Logran®</td>
</tr>
<tr>
<td></td>
<td>Tribenuron</td>
<td>Express®</td>
</tr>
<tr>
<td></td>
<td>Trifloxysulfuron</td>
<td>Envoke®</td>
</tr>
</tbody>
</table>
2B.1 Mode of action and biochemical pathways

Group B herbicides block the ALS enzyme essential in the production of the branched-chain fatty acids (amino acids) leucine, isoleucine and valine. These amino acids are essential for the production of proteins and for normal plant growth, while also providing precursors for a number of secondary products such as cyanogenic glycosides, glucosinolates and acyl-sugars.

A detailed explanation of branched chain fatty acid synthesis can be found here at the Plant & Soil Sciences eLibrary: http://passel.unl.edu/pages/informationmodule.php?idinformationmodule=980466115&topicorder=2&maxter=4

This process occurs within the chloroplasts. Once the ALS enzyme is blocked, plant growth quickly stops with the cessation of cell division. There can also be a buildup of the intermediate molecule alpha ketobutyrate, which is toxic, plus a decrease in phloem transport. Group B herbicides can therefore self-limit their translocation within the plant.

2B.2 Absorption into the plant

Group B herbicides are weak acid herbicides with moderate water solubility (Table 2) and are absorbed via the leaves and the roots, using the aqueous pathway.

<table>
<thead>
<tr>
<th>Group B class</th>
<th>Active ingredient</th>
<th>Example trade name</th>
<th>Water solubility (mg/L)</th>
<th>Log $K_{ow}$</th>
<th>Persistence in soil (half-life @ 20°C) (days)</th>
<th>Soil mobility ($K_{oc}/K_{foc}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imidazolinones</td>
<td>Imazamox</td>
<td>Raptor®</td>
<td>626,000</td>
<td>5.36</td>
<td>17</td>
<td>Very mobile</td>
</tr>
<tr>
<td></td>
<td>Imazapic</td>
<td>Flame®</td>
<td>2230</td>
<td>2.47</td>
<td>232</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>Imazapyr</td>
<td>Arsenal®</td>
<td>9740</td>
<td>0.11</td>
<td>11</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>Imazethapyr</td>
<td>Spinnaker®</td>
<td>1400</td>
<td>1.49</td>
<td>51</td>
<td>Mobile</td>
</tr>
<tr>
<td>Sulfonylureas</td>
<td>Chlorsulfuron</td>
<td>Lusta®</td>
<td>12,500</td>
<td>−0.99</td>
<td>36</td>
<td>Mobile</td>
</tr>
<tr>
<td></td>
<td>Metsulfuron</td>
<td>Ally®</td>
<td>2790</td>
<td>−1.87</td>
<td>13</td>
<td>Very mobile</td>
</tr>
<tr>
<td></td>
<td>Triasulfuron</td>
<td>Logran</td>
<td>8015</td>
<td>−0.59</td>
<td>39</td>
<td>Very mobile</td>
</tr>
<tr>
<td></td>
<td>Iodosulfuron</td>
<td>Hussar®</td>
<td>25,000</td>
<td>−0.7</td>
<td>3</td>
<td>Mobile</td>
</tr>
<tr>
<td>Sulfonamides</td>
<td>Florasulam</td>
<td>Paradigm®</td>
<td>6360</td>
<td>−1.22</td>
<td>9</td>
<td>Mobile</td>
</tr>
<tr>
<td></td>
<td>Flumetsulam</td>
<td>Broadstrike®</td>
<td>5650</td>
<td>0.21</td>
<td>45</td>
<td>Mobile</td>
</tr>
<tr>
<td></td>
<td>Metosulam</td>
<td>Eclipse®</td>
<td>700</td>
<td>0.2</td>
<td>39</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>Pyroxsulam</td>
<td>Crusader®</td>
<td>3200</td>
<td>−1.01</td>
<td>13</td>
<td>Mobile</td>
</tr>
</tbody>
</table>

Log $K_{ow}$ ratio of herbicide that is soluble in octanol (organic solvent) v. water. It is a good indicator of the lipophilic or hydrophilic nature of a herbicide; the larger the log $K_{ow}$ value the more lipophilic the herbicide. herbicides with values between −1 and 1 should move in the phloem following foliar application. $K_{oc}/K_{foc}$ >1000, binds strongly to soil; <500, moves in water. Solubility will vary with temperature and to a lesser degree pH.

2B.3 Translocation within the plant

Group B herbicides are weak acids. Weak acids are compounds containing a functional group, usually a carboxylic acid. This functional group gains or loses a hydrogen ion depending on the pH of the surrounding solution (for more details, see Herbicide GrowNotes: Group A).

Group B herbicides are readily transported within the phloem and xylem of plants, meaning that they are well translocated to the meristems of growing plants.

Sulfonylureas are preferentially transported in the xylem, and slower in the phloem, whereas imidazolinones are primarily transported in the phloem and less so in the xylem.

Sulfonamides are absorbed by the shoots and roots. Plants tolerant of the herbicide florasulam have reduced translocation from the leaves.

2B.4 Symptoms

Growth ceases quickly following foliar application on small plants and more slowly on larger plants. The initial symptoms include the yellowing of growing points. New upper leaves wilt. Mid-rib and veins of some dicots turn red. Plants that receive a sub-lethal dose remain stunted, often with a severely reduced root system.

Photo 1: SU residue effects on canola seedling, note stunting and reddening.

Photo: David Pfeiffer
Photo 2: Glean effects, yellowing of growing point on Albus lupins.
Photo: G. Shepard, IMAG Consulting

Photo 3: Spinnaker causing growing tips to yellow on field peas.
Photo: Penny Hewson
Photo 4:  Spinnaker damage in soybeans.
Photo: DPI&F

Photo 5:  Group B damage on a radish plant.
Photo: Andrew Storrie, Agronomo
2B.4.1 Timeframe for symptoms and plant death

Rate of development of symptoms and subsequent damage and death depend on the plant species, herbicide dose, age and size of plant, and rate of plant growth. Death occurs from as early as two weeks to around four–six weeks post-application. Plants that have received a sublethal dose often live until they are exposed to moisture stress from increasing temperatures and drying surface soil.

2B.5 Plant selectivity

Selectivity in crops and weeds is due to rapid detoxification, and in some instances (e.g. florasulam) is aided by slow translocation from the leaves to the growing points. There is a large variation in crop cultivar sensitivity to various Group B herbicides (Table 3). See the National Variety Trials Herbicide Tolerance web site for details.

Wheat, barley, canola and maize cultivars have been bred with additional tolerance to imidazolinone herbicides and are marketed as Clearfield® technology by BASF. The incorporation of Group B resistance into crops enables post-emergent application of registered imidazolinone herbicide combinations to these crops that would damage non-Clearfield® lines. Clearfield® cultivars also have the advantage of tolerating Group B soil residues that might be present following application to the previous crop. See below under the heading Soil activity for more information on soil residues.
Photo 7: Imi damage to conventional canola amongst imi tolerant lines. Herbicide sensitivity is exacerbated when plants are stressed due to cold, waterlogging or soil constraints because they are slower to metabolise the herbicide and exhibit damage symptoms and subsequent yield loss.

Table 3: Differences in selectivity between Group B chemical classes.

<table>
<thead>
<tr>
<th>Herbicide</th>
<th>Selective in some grass crops</th>
<th>Selective in some dicot crops</th>
<th>Non-selective (soil-applied pre-emergent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imidazolinones</td>
<td>Clearfield® only</td>
<td>Clearfield® canola</td>
<td>Imazapyr (higher rates)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Imazethapyr (faba beans, mungbeans, field peas, peanuts, soybeans, lucerne)</td>
<td></td>
</tr>
<tr>
<td>Sulfonylureas</td>
<td>Azimsulfuron (rice)</td>
<td>Rimsulfuron (tomatoes)</td>
<td>Sulfometuron</td>
</tr>
<tr>
<td></td>
<td>Chlorsulfuron</td>
<td>Trifloxysulfuron (cotton)</td>
<td>Tribenuron (fallow)</td>
</tr>
<tr>
<td></td>
<td>Ethoxysulfuron (sugarcane)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Iodosulfuron</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mesosulfuron</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Metsulfuron</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sulfosulfuron</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfonamides</td>
<td>Florasulam</td>
<td>Flumesulam (chickpeas, field peas, lentil)</td>
<td>Metosulam (lupins)</td>
</tr>
<tr>
<td></td>
<td>Flumesulam</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Metosulam (e.g. oats)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pyroxsulam</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
2B.6 Soil activity

Group B herbicides are soil-active because they are not strongly adsorbed to soil particles and have moderate water solubility, making them readily absorbed by plant roots.

2B.6.1 Imidazolinones

Imidazolinones are generally weakly bound to the soil but adsorption increases as organic matter and clay content increase. Adsorption increases as soil pH drops below 6.5. Persistence increases with declining pH.

Breakdown occurs through microbial degradation and low levels of photolysis on the soil surface.

2B.6.2 Sulfonylureas

Sulfonylureas have low adsorption to clay and high adsorption to soil organic matter. Non-microbial hydrolysis is high at pH < 6.5 but degradation rates are slow at pH 7.5–8.0. Therefore, persistence increases with increasing soil pH.

Degradation rates increase with increasing temperature and soil moisture. Microbial degradation is slow, but varies between herbicides. For example, tribenuron-methyl has higher levels of microbial breakdown than metsulfuron, so the former has a shorter plant-back period.
Sulfonamides are weakly bound to soils. Soil adsorption increases at lower pH. Primary mode of breakdown in the soil is microbial; therefore, rates are determined by temperature and available soil moisture.
2B.7 Effect of environmental conditions on activity

2B.7.1 Light
High light conditions can thicken the cuticle of a weed, which will increase the length of the aqueous absorption route, thus reducing rates and potentially total absorption by Group B herbicides.

Group B herbicides are rapidly decomposed by photolysis in water, reducing environmental hazards, but they experience low levels of photolysis on the soil surface.

Decreasing light intensity, such as occurs in autumn, increases the ratio of shoots to rhizomes in perennial species, which leads to better control through better herbicide interception and more herbicide translocating to the root system. There is also an increase in the amount of starches and sugars moving into roots and storage organs, which in turn increases the transport of phloem-mobile Group B herbicides.

2B.7.2 Temperature
As temperature increases, the rate of uptake of herbicide increases provided respiration and photosynthesis are not limited by the conditions. However, the total amount of herbicide absorbed does not change. High temperatures and low available soil moisture reduce herbicide translocation through the shutdown of transpiration.

However, higher temperatures with lower humidity speed the drying of spray droplets on the leaf, thus reducing time available for absorption. This effect can be reduced by the type of adjuvant used and by maintaining the applied herbicide rate.

Optimum temperatures for photosynthesis and respiration are determined by whether the plants use C3 or C4 photosynthesis. C3 plants grow best at temperatures <30°C, whereas C4 plants can actively grow at temperatures up to 35°C and at higher light intensities.

Frost and cold weather with prolonged low light (cloud) will cause increased levels of crop damage. Low soil temperatures have been found to worsen sulfonylurea damage to cereal crops. Increased crop damage results from lower production of P450 enzymes due to reduced crop growth, and therefore, the herbicide is deactivated more slowly within the crop plant.

A range of research has shown that Group B herbicides are highly efficacious at temperatures of 15°–25°C; however, this will vary between the herbicides. Some research has shown that control of wild radish (R. raphanistrum) with flumetsulam increased by 7.5 times when temperature increased from 13°C to 20°C. However, metosulam control increased by only <2% over a similar temperature range.

2B.7.3 Humidity
The main effect of humidity with Group B herbicides is that weeds will likely be actively growing and will quickly translocate the herbicide to the meristems. This assumes adequate soil moisture. High humidity and low soil moisture will slow transpiration and, therefore, photosynthesis and growth.

High humidity increases the rate of herbicide absorption by maintaining a hydrated leaf cuticle.

Plants growing under high humidity also have thinner cuticles and are generally easier to control because of quicker uptake of herbicide.

2B.7.4 Soil moisture stress
Stressed plants have thicker cuticles, which will increase the length of the aqueous path accessed by Group B herbicides. These additional waxes or hairs can increase herbicide runoff and droplet bounce, reducing herbicide coverage.
Moisture stress will reduce translocation of the herbicide and reduce herbicide efficacy. Addition of certain adjuvants can assist herbicide absorption into the plant; however, if the plant is not actively growing, translocation and efficacy will be limited. Research has shown that absorption of imazethapyr by common ragweed (Ambrosia artemisiifolia) under moisture stress was reduced by 10%, whereas translocation was unaffected. In the same experiment, humidity of 65–85% had no effect on absorption and translocation.

2B.7.5 Rain

Group B herbicides are rain-fast for 2–4 hours; however, because of their soil activity, weed control from herbicides such as chlorsulfuron has been found less affected by rain shortly after application. Weeds exposed to multiple days of rain have been found to modify cuticular waxes and improve herbicide absorption. Dew or light rain soon after application has been known to increase crop damage because it runs herbicide into the leaf axils, increasing the quantity of herbicide absorbed, which overwhelms the enzymes responsible for metabolising the herbicide before it reaches the meristem.

2B.8 Spray application

Group B herbicides are well translocated within the plant, so spray coverage appears less critical than with contact herbicides. The spray target should be at least 8% coverage. Label recommendations vary from a minimum application volume of 50 litres per hectare (L/ha) to 100–150 L/ha. Some imidazolinones have a minimum application volume of 70 L/ha. Spray quality on labels generally recommends medium to coarse.

2B.8.1 Adjuvants

Sulfonylureas and sulfonamides are generally formulated as dry flowable products. These contain a surfactant to improve droplet retention. Imidazolinones are produced as either soluble aqueous concentrates (e.g. Intervix®) or water-dispersible granules (e.g. Spinnaker® 700 WDG). All Group B herbicides are recommended to be applied with an adjuvant, except Londax® and Arsenal® Xpress. Read the label for recommended use of adjuvants.

2B.8.2 Water quality

Temperature

No data are available on the effect of low spray solution temperatures on efficacy.

pH

The effect of the pH of a spray solution is one of the most widely misunderstood concepts in spray application. Do not leave spray premixed overnight. Higher pH water is thought to improve slightly the efficacy of sulfonylurea herbicides.

Hardness

Despite Group B herbicides being weak acids, no evidence of the effect of hard water for spraying is available.
Turbidity

Muddy and water with low levels of algae pose a filter and nozzle blockage risk.

2B.9 Further reading


Herbicide Group C modes of action

The Group C Mode of Action (MoA) herbicides inhibit photosynthesis by blocking the action of photosystem II, through blocking the transfer of high-energy electrons needed by the plant to convert water and carbon dioxide to oxygen gas and sugars.

Group C herbicides are divided into three groups under the global Herbicide Resistance Action Committee (HRAC) and Weed Science Society of America (WSSA) systems, according to whether they block photosystem II at site A, B, or at site A with a different binding behaviour. Often there is no cross-resistance from one class to another, hence the three classifications. They are also classified as Groups C1, C2 and C3 by HRAC and Groups 5, 6 and 7 by WSSA (http://hrac.tsstaging.com/tools/classification-lookup).

There are nine chemical classes within the Group C MoA as shown in Table 1. These classes are different types of chemicals; however, they affect the same biochemical pathways in the plant.

Photo 1: The effects of atrazine on mungbeans

DPI&W
**Table 1: Herbicides included in Group C.**

<table>
<thead>
<tr>
<th>Chemical class</th>
<th>Active ingredient</th>
<th>Product examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amides</td>
<td>Propanil</td>
<td>Stam®</td>
</tr>
<tr>
<td>Benzothiadiazinones</td>
<td>Bentazon</td>
<td>Basagran®, Basagran® M60 (PM)</td>
</tr>
<tr>
<td>Nitriles</td>
<td>Bromoxynil</td>
<td>Buctril® MA (PM), Eliminar C® (PM), Flight® (PM), Jaguar® (PM), Triathlon® (PM), Velocity® (PM)</td>
</tr>
<tr>
<td></td>
<td>Ioxynil</td>
<td>Actril® DS (PM), Tore®</td>
</tr>
<tr>
<td>Phenylcarbamates</td>
<td>Phenmedipharm</td>
<td>Betanal®</td>
</tr>
<tr>
<td>Pyridazinones</td>
<td>Chloridazon</td>
<td>Pyramin®</td>
</tr>
<tr>
<td>Triazines</td>
<td>Ametryn</td>
<td>Amigan® (PM), Gesapax Combi® (PM), Krismat® (PM)</td>
</tr>
<tr>
<td></td>
<td>Atrazine</td>
<td>Gesapax Combi® (PM), Gesaprim®, Primextra Gold® (PM)</td>
</tr>
<tr>
<td></td>
<td>Cyanazine</td>
<td>Bladex®</td>
</tr>
<tr>
<td></td>
<td>Prometryn</td>
<td>Cotogard® (PM), Gesagard®</td>
</tr>
<tr>
<td></td>
<td>Propazine</td>
<td>No registered products</td>
</tr>
<tr>
<td></td>
<td>Simazine</td>
<td>Gesatop®</td>
</tr>
<tr>
<td></td>
<td>Terbuthylazine</td>
<td>Terbyne®</td>
</tr>
<tr>
<td></td>
<td>Terbutryn</td>
<td>Agtryne® MA (PM), Amigan® (PM), Igian®</td>
</tr>
<tr>
<td>Triazinones</td>
<td>Hexazinone</td>
<td>Bobcat® i-Maxx (PM), Velpar® K4™ (PM), Velpar® L</td>
</tr>
<tr>
<td></td>
<td>Metribuzin</td>
<td>Aptitude® (PM), Sencor®</td>
</tr>
<tr>
<td>Uracils</td>
<td>Bromacil</td>
<td>Hyvar®, Krovar® (PM)</td>
</tr>
<tr>
<td></td>
<td>Terbacil</td>
<td>Eucmix® PrePlant (PM), Sinbar®</td>
</tr>
<tr>
<td>Ureas</td>
<td>Diuron</td>
<td>Krovbar® (PM), Velpar® K4 (PM)</td>
</tr>
<tr>
<td></td>
<td>Fluometuron</td>
<td>Cotogard® (PM), Cotoran®</td>
</tr>
<tr>
<td></td>
<td>Linuron</td>
<td>Afalon®</td>
</tr>
<tr>
<td></td>
<td>Methabenzthiazuron</td>
<td>Tribunii®</td>
</tr>
<tr>
<td></td>
<td>Sidorun</td>
<td>Tupersan®</td>
</tr>
<tr>
<td></td>
<td>Tebuthiuron</td>
<td>Graslan®</td>
</tr>
</tbody>
</table>

PM. Product contains more than one active constituent; some products listed contain two active ingredients from one chemical class.


The Group C herbicides are some of the oldest synthetic herbicides, with atrazine first commercialised in 1957.

Group C herbicides are used on a large scale worldwide. They are used as pre- and post-emergent herbicides in a wide range of crops as well as for fallow and non-agricultural weed control.

### 2C.1 Mode of action and biochemical pathways

Group C herbicides inhibit photosynthesis by binding to the plastoquinone (QB) binding niche on the D1 proteins of the photosystem II complex in the chloroplast thylakoid membranes. Herbicide binding at this location blocks electron transport from QA to QB and stops carbon dioxide fixation and the production of ATP and NADPH2. These are needed for plant growth. Photosynthesis is effectively stopped, however, plant death occurs by a number of processes.
The inability to readily oxidise QA promotes the formation of triplet-state chlorophyll, which interacts with oxygen to form singlet oxygen. Both triplet chlorophyll and singlet oxygen can extract hydrogen from unsaturated lipids, producing a lipid radical and initiating a chain reaction of lipid peroxidation. Lipids and proteins are attacked and oxidised, resulting in loss of chlorophyll and carotenoids and in leaky membranes that dry and disintegrate cells.

Some compounds in this group may inhibit carotenoid synthesis (e.g. fluometuron) or synthesis of anthocyanin, RNA and proteins as well as causing disruption of the plasmalemma (e.g. propanil).

These herbicides require sunlight to work effectively. The more sunlight available the faster the symptoms develop.

### 2C.2 Absorption into the plant

Most Group C herbicides have a moderate level of water solubility (Table 2). Some are also weak acids. This means that they are absorbed through the aqueous route of the cuticle and through the roots.

<table>
<thead>
<tr>
<th>Group class</th>
<th>Active ingredient</th>
<th>Example trade name</th>
<th>Water solubility (mg/L)</th>
<th>Log K&lt;sub&gt;ow&lt;/sub&gt;</th>
<th>Soil persistence (half life @ 20°C) (days)</th>
<th>Soil mobility (K&lt;sub&gt;oc&lt;/sub&gt;/K&lt;sub&gt;foc&lt;/sub&gt;)</th>
<th>Volatility (Henry’s Law constant, 25°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amides</td>
<td>Propanil</td>
<td>Stam®</td>
<td>95</td>
<td>2.29</td>
<td>0.4</td>
<td>152, moderate</td>
<td>Non-volatile</td>
</tr>
<tr>
<td>Benzothiadiazinones</td>
<td>Bentazon</td>
<td>Basagran®</td>
<td>7112</td>
<td>–0.46</td>
<td>75</td>
<td>55, mobile</td>
<td>Non-volatile</td>
</tr>
<tr>
<td>Nitriles</td>
<td>Bromoxynil</td>
<td>Bronco® 400</td>
<td>0.05</td>
<td>6.2</td>
<td>8</td>
<td>24,739, non</td>
<td>Non-volatile</td>
</tr>
<tr>
<td>Triazines</td>
<td>Atrazine</td>
<td>Gesaprim®</td>
<td>35</td>
<td>2.7</td>
<td>29</td>
<td>100, moderate</td>
<td>Non-volatile</td>
</tr>
<tr>
<td></td>
<td>Prometryn</td>
<td>Cotagard®</td>
<td>33</td>
<td>3.34</td>
<td>41</td>
<td>400, moderate</td>
<td>Non-volatile</td>
</tr>
<tr>
<td></td>
<td>Simazine</td>
<td>Gesatop®</td>
<td>5</td>
<td>2.3</td>
<td>90</td>
<td>130, moderate</td>
<td>Non-volatile</td>
</tr>
<tr>
<td></td>
<td>Terbuthylazine</td>
<td>Terbyne®</td>
<td>7</td>
<td>3.4</td>
<td>23</td>
<td>231, moderate</td>
<td>Non-volatile</td>
</tr>
<tr>
<td></td>
<td>Terbutryn</td>
<td>Igran®</td>
<td>25</td>
<td>3.66</td>
<td>52</td>
<td>2432, slight</td>
<td>Non-volatile</td>
</tr>
<tr>
<td>Triazinones</td>
<td>Hexazinone</td>
<td>Velpar®</td>
<td>33,000</td>
<td>117</td>
<td>60</td>
<td>54, mobile</td>
<td>Non-volatile</td>
</tr>
<tr>
<td></td>
<td>Metribuzin</td>
<td>Sencor®</td>
<td>1165</td>
<td>1.65</td>
<td>19</td>
<td>38, mobile</td>
<td>Non-volatile</td>
</tr>
<tr>
<td>Uracils</td>
<td>Bromacil</td>
<td>Hyvar®</td>
<td>815</td>
<td>118</td>
<td>60</td>
<td>32, mobile</td>
<td>Non-volatile</td>
</tr>
<tr>
<td></td>
<td>Terbacil</td>
<td>Sinbar®</td>
<td>710</td>
<td>1.89</td>
<td>120</td>
<td>55, mobile</td>
<td>Non-volatile</td>
</tr>
<tr>
<td>Ureas</td>
<td>Diuron</td>
<td>Diurex®</td>
<td>36</td>
<td>2.87</td>
<td>89</td>
<td>813, slight</td>
<td>Non-volatile</td>
</tr>
<tr>
<td></td>
<td>Fluometuron</td>
<td>Cotoran®</td>
<td>111</td>
<td>2.28</td>
<td>90</td>
<td>67, mobile</td>
<td>Non-volatile</td>
</tr>
<tr>
<td></td>
<td>Linuron</td>
<td>Aforon®</td>
<td>64</td>
<td>3</td>
<td>48</td>
<td>843, slight</td>
<td>Non-volatile</td>
</tr>
<tr>
<td></td>
<td>Methabenzthiazuron</td>
<td>Tribunil®</td>
<td>60</td>
<td>2.64</td>
<td>.35</td>
<td>527, slight</td>
<td>Non-volatile</td>
</tr>
</tbody>
</table>

Log K<sub>ow</sub>, ratio of herbicide that is soluble in octanol (organic solvent) v. water. It is a good indicator of the lipophilic or hydrophilic nature of a herbicide; the larger the log K<sub>ow</sub> value the more lipophilic the herbicide; herbicides with values between –1 and 1 should move in the phloem following foliar application. K<sub>oc</sub>/K<sub>foc</sub> >1000; binds strongly to soil; <500, move in water. Solubility will vary with temperature and to a lesser degree pH.


### 2C.3 Translocation within the plant

Once inside the plant, Group C herbicides move almost exclusively within the xylem and have limited downward movement in the phloem. Although these herbicides are readily absorbed by the leaves, they accumulate on the margins of the leaf as they are moved there within the xylem. This is where the first symptoms appear.
2C.4 Symptoms

Symptoms begin with interveinal yellowing of the leaves and yellowing of the leaf margins. This yellowing spreads and turns to necrosis or browning. Older leaves are usually more affected than new growth.

With herbicides such as bromoxynil there tends to be a general yellowing of the leaves followed by necrosis. Bromoxynil essentially acts as a knockdown/contact herbicide.
Photo 3: Atrazine damage on a sorghum plant.
Photo: Andrew Storrie, Agronomo

Photo 4: Older leaves of canola showing the effects of Metribuzin.
Photo: Harm van Rees
Photo 5: Atrazine damage in sunflowers.
Photo: NSW DPI

Photo 6: Mecrosis on a soybean leaf from Cotoguard (prometryn + fluometuron).
Photo: DPI&F
2C.4.1 Timeframe for symptoms and plant death

Rate of development of symptoms and subsequent damage and death depend on the plant species, herbicide dose, age and size of plant, and rate of plant growth. Death occurs from as early as two weeks to around four–six weeks post-application.

- With foliar applications, interveinal chlorosis can begin within 2 days with foliar necrosis in 3–6 days.
- Symptom development in soil-absorbed herbicides is often slower because the herbicides need to be moved via the xylem to the leaves. This is strongly related to rate of plant growth and availability of soil moisture. If seeds germinate in the band of herbicide, they absorb herbicide as the seedling grows, and need at least two true leaves to accumulate a lethal dose.

2C.5 Crop selectivity

Selectivity within Group C herbicides is based on differential herbicide application rates and pathways of herbicide metabolism in the crops and weeds (Table 3). Species selectivity is conferred by rapid herbicide metabolism to non-toxic compounds by the crop but not the weed. Because of their poor phloem translocation, they are effectively burn-down herbicides when applied as a post-emergent treatment.

Selectivity of many herbicides is rate-dependent; they are non-selective at high application rates and selective at lower application rates. Diuron is an excellent example and is used as a selective post-emergent herbicide in winter cereal crops at low rates but is used for total vegetation control at high rates.

Selectivity of triazines occurs by several different processes. Truly tolerant species such as maize and sorghum metabolise triazines by a rapid enzymic process called glutathione conjugation, whereas partly tolerant species such as field peas (and wheat) use a slower N-dealkylation degradation. Some species have a degree of tolerance because their roots do not absorb the chemicals efficiently. If they also develop deep root systems rapidly, they will outgrow any herbicide damage from triazines. This is thought to be the main mechanism for tolerance in lupins.
lupin taproot has been damaged by root disease, the plant is forced to survive on secondary roots growing in the surface soil. Consequently, the roots absorb more herbicide than normal and the lupin plant exhibits symptoms of triazine damage.

Photo 8: Triazine damage to a lupin plant. Placement selectivity enables triazines to be used to control annual weeds near established trees. Very little of the surface-applied herbicide is taken up by the tree roots while annual weeds are controlled. However, heavy rainfall can move the herbicide into the root-zone of the trees. This causes increased herbicide absorption, which leads to tree damage and sometimes death.

Photo: Tom De Matia, Delta Agribusiness

Bentazone is rapidly metabolised in tolerant species to form glucosyl conjugates.

The uracil herbicides bromacil and terbacil are not metabolised within the plant and are largely non-selective. They are used for total vegetation control. Selectivity of bromacil in orange trees is due to the low levels of root absorption and compartmentalisation of herbicide absorbed within the roots.

Selectivity of bromoxynil is due to a number of factors including higher levels of spray retention and increased absorption by broadleaf species, less contact with cereal growing points, and differences in the rate of metabolism. Selectivity of bromoxynil decreases at temperatures ≥20°C, leading to damage in otherwise tolerant species.
Table 3: Differences in efficacy between Group C chemical classes

<table>
<thead>
<tr>
<th>Group C class</th>
<th>Herbicide example</th>
<th>Crops</th>
<th>Weeds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amides</td>
<td>Propanil</td>
<td>Rice</td>
<td>Post-emergent control of barnyard grass</td>
</tr>
<tr>
<td>Benzothiadiazinones</td>
<td>Bentazone</td>
<td>Summer pulses</td>
<td>Post-emergent control of broadleaf weeds</td>
</tr>
<tr>
<td>Nitriles</td>
<td>Bromoxynil</td>
<td>Winter cereals, grain sorghum, linseed, clover, lucerne, turf</td>
<td>Post-emergent control of broadleaf weeds</td>
</tr>
<tr>
<td>Triazines</td>
<td>Atrazine</td>
<td>Triazine-tolerant canola, <em>Pinus</em> spp., <em>Eucalyptus</em> spp., grass pastures, lucerne, lupins, maize, sorghum, millet, sugarcane</td>
<td>Pre- and post-emergent, Range of grass and broadleaf species</td>
</tr>
<tr>
<td>Triazinones</td>
<td>Metribuzin</td>
<td>Barley, oats, wheat (limited), chickpeas, faba beans, lentils, lupins, field peas, pigeon peas, potatoes, soybeans, tomatoes</td>
<td>Range of broadleaf weeds and suppression of some annual grasses</td>
</tr>
<tr>
<td>Uricils</td>
<td>Bromacil</td>
<td>Total vegetation control and some crops</td>
<td>All seedlings and annual weeds</td>
</tr>
<tr>
<td>Ureas</td>
<td>Diuron</td>
<td>Asparagus, bananas, cotton (banded), established lucerne, winter pulses, sugarcane, wheat, irrigation channels</td>
<td>Wide range of annual broadleaf and grass weeds</td>
</tr>
</tbody>
</table>

Group C herbicides are often used in tank mixes to broaden the number of species controlled and to improve control on larger weeds. For example, the phenoxy MCPA is often combined with diuron to broaden the control spectrum as an early post-emergent treatment in wheat. Bromoxynil is also premixed with MCPA to broaden the control spectrum and improve herbicide robustness.

For total vegetation control, Group C herbicides are best applied to bare ground or small weeds only, because of their limited translocation in the phloem.

There is also some synergy between some Group C herbicides and Group I or H when used in tank mixes. That is, the effect of these tank mixes is greater than the additive effects.

Some research has also shown that adding either metribuzin or diuron to paraquat improves the control of glyphosate- and glufosinate-resistant maize up to the V4 stage compared with paraquat alone.

### 2C.6 Effect of environmental conditions on activity

Group C herbicides have moderate water solubility and some are weak acids, so they enter the plants via the aqueous pathway. Absorption and translocation of post-emergent applications will be affected by temperature, relative humidity and moisture stress.

Soil (pre-emergent) applications will be greatly affected by available soil moisture. The herbicide must be dissolved in the soil-water matrix to be absorbed by the roots, and uptake and transport in the xylem is dependent upon sufficient soil water to support actively growing plants.
2C.6.1 Light

High light conditions can thicken the cuticle of a weed, which will in turn reduce the uptake of water-soluble formulations.

Bentazone is more rapidly absorbed and translocated under conditions of high than low light intensity, whereas other herbicides such as ioxynil and bromoxynil are more active at lower light intensities. Ioxynil and bromoxynil act as post-emergent contact
herbicides and low light conditions might inhibit the plant’s ability to regrow after spraying. On the other hand, the efficacy of soil-applied group C herbicides increases with light intensity.

2C.6.2 Temperature

As temperature increases, the rate of uptake of foliar-applied herbicide increases provided respiration and photosynthesis are not limited by the conditions. However, the total amount of herbicide absorbed does not change. High temperatures and low available soil moisture reduce herbicide translocation through the shutdown of transpiration. Performance of foliar-applied bromoxynil and ioxynil increases with increasing temperature.

2C.6.3 Humidity

Plants growing in conditions of higher humidity have less epidermal wax on the leaf surface than plants growing in low humidity. High humidity hydrates the cuticle, allowing a continuous aqueous path to the epidermis for these water-soluble herbicides.

2C.6.4 Soil moisture stress

Moisture-stressed plants have thicker cuticles that will slow the absorption of foliar-applied Group C herbicides. Addition of certain adjuvants can assist herbicide absorption into the plant.

Low soil-moisture conditions reduce root absorption and translocation of soil-applied Group C herbicides.

In addition, photosynthesis will be limited, which will slow the activity of the herbicide, reducing levels of control.

2C.6.5 Rainfall

The rain-fast period for foliar application of Group C herbicides varies from three to eight hours.

For pre-emergent applications, labels can warn not to apply the herbicide if significant rain is pending. Heavy rains following application can move the herbicide into the root-zone and increase crop damage. The risk will vary with the water solubility of the herbicide. For example, simazine is far less water-soluble than atrazine, so atrazine will present a higher risk of crop damage. Potential damage will be higher on light-textured soils.

2C.7 Spray application

Foliar applied of Group C herbicides require very good coverage because these herbicides are effectively contact herbicides with little downward translocation. Newer labels are recommending that they be applied as a coarse spray quality; therefore, application volumes need to be kept above 70 litres per hectare to ensure adequate coverage.

Target coverage should be towards 15% as measured with water-sensitive paper.

Soil-applied herbicides need even coverage; however, they can be applied in a coarse to extremely coarse spray quality. If tank-mixed with a knockdown herbicide, they should be applied in the relevant spray quality for that knockdown herbicide.

2C.7.1 Adjuvants

Read the label for recommended use of adjuvants. Foliar applications of Group C herbicides often require an adjuvant to improve retention and absorption of the herbicide. Adjuvants can vary from a non-ionic surfactant to a spray oil.
Soil-applied Group C herbicides do not require an adjuvant.

### 2C.7.2 Water quality

**pH**

Spray acidity or alkalinity is largely irrelevant with these herbicides as long as they are in the normal range of pH 5–7.5.

**Hardness**

Because these herbicides can be weak acids, water hardness can be important. The presence of calcium and magnesium ions should be treated with ammonium sulfate.

**Salinity**

Diuron can be affected by high salinity levels, as can a tank mix of diuron plus MCPA.

**Turbidity**

Group C herbicides are generally not affected by the presence of clay and particulate matter in the spray solution; however, water of this quality should be treated to reduce blocking of filters and nozzles.

### 2C.8 Further reading


Herbicide Group D modes of action

The Group D Mode of Action (MoA) herbicides inhibit cell division by blocking the production of protein ropes (microtubule fibres) that separate chromosome duplicates during cell division.

Group D herbicides are also classified as Groups K1 by the global Herbicide Resistance Action Committee (HRAC) and Group 3 by the Weed Science Society of America (WSSA) (http://hrac.tsstaging.com/tools/classification-lookup).

There are four chemical classes within the Group D MoA as shown in Table 1. These classes are different types of chemicals; however, they affect the same biochemical pathways in the plant.

Table 1: Herbicides included in Group D.

<table>
<thead>
<tr>
<th>Chemical class</th>
<th>Active ingredient</th>
<th>Product examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzamide</td>
<td>Propyzamide</td>
<td>Kerb®</td>
</tr>
<tr>
<td>Benzoic acid</td>
<td>Chlorthal-dimethyl</td>
<td>Dacthal®</td>
</tr>
<tr>
<td>Dinitroanilines</td>
<td>Oryzalin</td>
<td>Surflan®</td>
</tr>
<tr>
<td></td>
<td>Pendimethalin</td>
<td>Stomp®</td>
</tr>
<tr>
<td></td>
<td>Trifluralin</td>
<td>Treflan®</td>
</tr>
<tr>
<td>Pyridines</td>
<td>Dithiopyr</td>
<td>Dimension®</td>
</tr>
</tbody>
</table>


The Group D herbicides are some of the oldest synthetic herbicides, first commercialised in 1961.

Group D herbicides are mostly used for pre-emergent control of a range of grass and broadleaf weeds in a wide range of field crops, horticulture, pastures and turf. Herbicides such as propyzamide have limited post-emergent activity on small weeds.

2D.1 Mode of action and biochemical pathways

Group D herbicides bind to tubulin, the major microtubule protein. This tubulin–herbicide complex stops the assembly of microtubules but does not prevent their deconstruction. This leads to a loss of microtubule structure and function, stopping formation of the spindle apparatus during cell division and hence preventing the alignment and separation of chromosomes to be distributed between the ‘daughter’ cells. Because microtubules also function in the formation of cell walls, this also stops cell division. This is expressed as the swelling of root tips as cells in this region neither divide nor elongate.
2D.2 Absorption into the plant

Group D herbicides are primarily absorbed by the emerging plant shoots (grass coleoptile, hypocotyl or epicotyls of dicots) or secondarily by the seedling roots. Some absorption of dinitroaniline vapour may occur. Trifluralin binds tightly to the lipid components of cell membranes.

![Photo 1: Wheat seedlings stunted and struggling to emerge from the coleoptile due to trifluralin.](image)

Photo: Harm van Rees

2D.3 Translocation within the plant

There is little translocation of Group D herbicides within the plant owing to their strong lipophilic nature (Table 2).

Established plants readily absorb trifluralin into the roots but upward movement in the plant is limited. The highly lipophilic nature of trifluralin means that it is rapidly absorbed into membranes and other parts of root tissues, limiting its translocation to the shoots. Trifluralin will have little effect when applied to the foliage of a plant.

Propyzamide is readily absorbed into the roots and distributed throughout the plant by upward translocation in the apoplast (includes the xylem). It also has foliar activity on seedlings of some weed species. Translocation of foliar-applied propyzamide is minimal.
Table 2: Environmental characteristics of Group D herbicides.

<table>
<thead>
<tr>
<th>Group class</th>
<th>Active ingredient</th>
<th>Example trade name</th>
<th>Water solubility (mg/L)</th>
<th>Log K&lt;sub&gt;ow&lt;/sub&gt;</th>
<th>Soil persistence (half-life @ 20°C) (days)</th>
<th>Soil mobility (K&lt;sub&gt;soil&lt;/sub&gt;/K&lt;sub&gt;foc&lt;/sub&gt;)</th>
<th>Volatility (Henry’s Law constant, 25°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzamide</td>
<td>Propyzamide</td>
<td>Kerb™</td>
<td>9</td>
<td>3.3</td>
<td>233</td>
<td>840, slightly</td>
<td>Non-volatile</td>
</tr>
<tr>
<td>Benzoic acid</td>
<td>Chlorthal-dimethyl</td>
<td>Dacthal®</td>
<td>0.21</td>
<td>4.3</td>
<td>47</td>
<td>2963, slightly</td>
<td>Moderately volatile</td>
</tr>
<tr>
<td>Dinitroanilines</td>
<td>Oryzalin</td>
<td>Surflan®</td>
<td>1.13</td>
<td>3.7</td>
<td>98</td>
<td>949, slightly</td>
<td>Non-volatile</td>
</tr>
<tr>
<td></td>
<td>Pendimethalin</td>
<td>Stomp®</td>
<td>0.3</td>
<td>5.4</td>
<td>101</td>
<td>17,490, non</td>
<td>Non-volatile</td>
</tr>
<tr>
<td></td>
<td>Trifluralin</td>
<td>Treflan™</td>
<td>0.2</td>
<td>5.3</td>
<td>170</td>
<td>15,800, non</td>
<td>Volatile</td>
</tr>
<tr>
<td>Pyridines</td>
<td>Dithiopyr</td>
<td>Dimension®</td>
<td>1.4</td>
<td>5.9</td>
<td>39</td>
<td>801, slightly</td>
<td>Non-volatile</td>
</tr>
</tbody>
</table>

Log K<sub>ow</sub> is the ratio of herbicide that is soluble in octanol (organic solvent) v. water. It is a good indicator of the lipophilic or hydrophilic nature of a herbicide; the larger the log K<sub>ow</sub> value the more lipophilic the herbicide; herbicides with values between –1 and 1 should move in the phloem following foliar application. K<sub>soil</sub>/K<sub>foc</sub> >1000, binds strongly to soil; <500, moves in water. Solubility will vary with temperature and to a lesser degree pH.


2D.4 Symptoms

Susceptible small-seeded annual grasses and broadleaf weeds fail to emerge, however, seed germination is not inhibited. Established plants have stunted root systems with deformed and swollen root tips. Grass stems may be purple at the base. The base of grass stems may also become swollen. Shoots may be deformed and brittle.

Photo 2: Wheat seedlings with shortened coleoptiles and stunted root systems from 2 L trifluralin/Ha.

Photo: David Pfeiffer
Photo 3: Propyzamide damage in TT canola.

Photo: David Pfeiffer

Photo 4: Shortened coleoptiles in wheat leading to the first true leaf to struggle with emergence. Leaves can look consortia-like from trifluralin.

Photo: Bill Long
Photo 5: Ryegrass roots severely stunted from propyzamide.
Photographer: Andrew Storrie, Agronomo

Photo 6: Propyzamide affecting oat plants.
Photographer: Andrew Storrie, Agronomo
2D.4.1 Timeframe for symptoms and plant death

Seeds that germinate within the soil–herbicide layer and absorb the herbicide do not emerge as long as there is sufficient soil moisture to activate the herbicide.

Plants that germinate above the herbicide layer can establish but have their root systems stunted. These plants can grow leaves and shoots until they undergo moisture stress in spring, then they die.

Plants germinating below the herbicide layer or managing to germinate in the herbicide layer with insufficient moisture to activate the herbicide can also establish and grow as long as their meristems grow beyond the treated layer. This can take between two weeks and several months depending on growing conditions and species.

2D.5 Crop selectivity

Selectivity in Group D herbicides is not based on metabolism but it is based on:
- almost no translocation within the plant (due to a highly lipophilic nature)
- depth of soil incorporation
- the differing position of the meristematic region of weed and crop.

2D.5.1 Grass weeds and cereal crops

Primary roots and the coleoptile node are the active sites in cereal crops and grass weeds. The position of the primary root is the same in crops and grass weeds, but the position of the coleoptile node will vary. For example, wild oats push the coleoptile upward (have a mesocotyl), which pushes the Group D-sensitive coleoptile node into the herbicide-treated soil. Wheat and barley do not have a mesocotyl, so the coleoptile node remains below the herbicide-treated soil.

With the development of direct seeding of crops, the pattern of use for trifluralin has changed. The original use pattern consisted of a trifluralin rate of less than one litre per hectare (L/ha), which was then incorporated within four hours of application to the top 50 mm of soil. With direct planting techniques, the application rate is 1.5–3 L/ha, applied within 24 hours of planting. The higher herbicide rate is required if significant crop residues are present and to account for vapour losses before incorporation. To maintain crop safety, a tined machine is needed to push herbicide-treated soil away from the crop row. This has the disadvantage of removing the herbicide from the crop row, which allows weeds to germinate and establish.
2D.5.2 Broadleaf weeds and crops

Selectivity between broadleaf crops and weeds is poorly understood; however, there is some evidence that plants that have seeds with high oil content somehow tolerate Group D herbicides. Another theory suggests less root uptake in certain broadleaf species.

Wireweed (Polygonum aviculare), tree hogweed (P. bellardii), poppies (Papaver spp.) and black bindweed (Fallopia convolvulus) are particularly sensitive to the dinitroaniline herbicides (Table 3).
Table 3: Differences in efficacy between Group D chemical classes.

<table>
<thead>
<tr>
<th>Group D class</th>
<th>Herbicide example</th>
<th>Crops</th>
<th>Weeds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzamide</td>
<td>Propyzamide</td>
<td>Canola, legume pastures, oilseed poppies, lettuce, turf</td>
<td>Mostly pre-emergent control: annual ryegrass, barley grass, Canary grass, fescue, great brome, prairie grass, <em>Vulpia</em> spp., wild oats, winter grass, Bent grass, blackberry, nightshade, chickweed, English couch, Paterson's curse, perennial ryegrass, seedling sorrel, seedling wireweed, Yorkshire fog grass</td>
</tr>
<tr>
<td>Benzoic acid</td>
<td>Chlorthal-dimethyl</td>
<td>Brassicas, green beans, field peas, garlic, onions, carrots, lettuce, potatoes, turnips, and for weed control in strawberries, cotton, lucerne, perennial grass crops, lawns and ornamentals</td>
<td>Pre-emergent control of a wide range of grass and broadleaf weeds, Can apply over established turf</td>
</tr>
<tr>
<td>Dinitroanilines</td>
<td>Oryzalin</td>
<td>Fruit and nut orchards, vineyards, nursery stock, ornamental and amenity plantings</td>
<td>Pre-emergent control of wide range of grass and broadleaf weeds</td>
</tr>
<tr>
<td></td>
<td>Pendimethalin</td>
<td>Barley, wheat, chickpeas, faba beans, field peas, lentils, lupins, safflower, soybeans, peanuts, navy beans, cow peas, mungbeans, pigeon peas, cotton, carrots, processing peas, onions, sugarcane, drill-sown rice, perennial crops plus others</td>
<td>Mainly pre-emergent control of a wide range of grass and broadleaf weeds, Can apply over the top of eucalypts, pyrethrum, oil tea-tree, established lucerne, turf</td>
</tr>
<tr>
<td>Trifluralin</td>
<td></td>
<td>Wheat, barley, triticale, canola, chickpeas, adzuki beans, cowpeas, lablab, mungbeans, borlotti beans, red kidney beans, faba beans, pigeon peas, lentils, navy beans, soybeans, vetch, cotton, sugarcane, linseed, field peas, peanuts, sunflowers, lupins, tobacco plus others</td>
<td>Pre-emergent control of wide range of grass and broadleaf weeds</td>
</tr>
<tr>
<td>Pyridines</td>
<td>Dithiopyr</td>
<td>Turf</td>
<td>Pre-emergent control of <em>Digitaria</em> spp., <em>Echinochloa</em> spp., <em>Eleusine indica</em>, <em>Stellaria media</em></td>
</tr>
</tbody>
</table>
2D.6  Effect of environmental conditions on activity

The main environmental conditions affecting the activity of Group D herbicides are temperature and available soil moisture.

Several researchers in Australia and Europe have found that degradation of propyzamide accelerates with use. One team found that soil half-life declined from 31 days in previously untreated soil to 10 days on plots treated 14 times. This is thought to be due to increased microbial degradation. This effect will translate to shorter periods of effective weed control with propyzamide.

Overseas, propyzamide has been found in drinking water and its use is under review.

2D.6.1 Temperature

Warmer temperatures increase the rate of cell division and therefore the rate of plant deformation, because Group D herbicides affect cell division.

The rate of volatilisation of trifluralin and chlorthal-dimethyl from the soil surface increases with increasing temperature.

2D.6.2 Soil moisture

Adequate soil moisture in the herbicide layer is essential for absorption of the herbicides into the plant meristems. Dry soils tend to favour weeds to emerge through the herbicide layer. Trifluralin is thought to form a vapour in the presence of soil moisture, which is then absorbed into the plant meristem. Without adequate soil moisture, trifluralin remains tightly bound to the soil particles. Application of trifluralin to moist soils without incorporation leads to large herbicide losses via volatilisation.

2D.6.3 Rainfall

Most Group D herbicides are tightly bound to soil particles and organic matter. There is little leaching with Group D herbicides; however, there can be some incorporation of pendimethalin, oryzalin, propyzamide and chlorthal-dimethyl with 12–25 mm of rain or irrigation.

2D.7  Spray application

Group D herbicides require even coverage of the soil because there is little movement once applied. Most labels recommend a minimum application volume of 70 L/ha, although label recommendations range from 50 to 200 L/ha. The greater the amount of crop residue present, the higher the application volumes recommended.

Although not mentioned on labels, the best penetration of standing stubble is achieved by application with the finer end of coarse spray quality. Droplets of this size have sufficient momentum to penetrate the canopy but not so much momentum (such as with extremely coarse droplets) that they ‘crash’ into the stubble and paint it with herbicide. If little crop residue is present, extremely coarse droplets can be used.

Target coverage should be towards 15% as measured with water-sensitive paper.

2D.7.1 Adjuvants

Read the label for recommended use of adjuvants. Generally, adjuvants are not required unless the Group D herbicides are being applied in a tank mix and the tank mix partner requires an adjuvant.

2D.7.2 Water quality

Group D herbicides are not sensitive to water quality.
2D.8 Further reading


Herbicide Group F modes of action

The Group F Mode of Action (MoA) herbicides inhibit carotenoid biosynthesis by blocking the phytoene desaturase enzyme. Symptoms include the bleaching of new growth.

Group F herbicides are also classified as Group 12 by the global Herbicide Resistance Action Committee (HRAC) and Group F1 by the Weed Science Society of America (WSSA) (http://hrac.tsstaging.com/tools/classification-lookup).

There are two chemical classes within the Group F MoA as shown in Table 1. These classes are different types of chemicals; however, they affect the same biochemical pathways in the plant.

Table 1: Herbicides included in Group F.

<table>
<thead>
<tr>
<th>Chemical class</th>
<th>Active ingredient</th>
<th>Product examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyridazinones</td>
<td>Norflurazon</td>
<td>Zoliar®</td>
</tr>
<tr>
<td>Pyridinecarboxamide</td>
<td>Diflufenican</td>
<td>Brodal®, Spearhead® (PM), Jaguar® (PM), Tigrex® (PM), Triathlon® (PM)</td>
</tr>
<tr>
<td></td>
<td>Picolinafen</td>
<td>Sniper®, Eliminar™ C (PM), Flight® (PM), Paragon®</td>
</tr>
</tbody>
</table>

PM, Product contains more than one active constituent.

Norflurazon was the first of the Group F herbicides and was commercialised in 1968, whereas diflufenican was commercialised in 1990.

Norflurazon is used as a pre-emergent herbicide in a wide range of field and horticultural crops for the control of grasses, sedges and broadleaf weeds. Diflufenican and picolinafen are used for post-emergent control of broadleaf weeds in pulses and legume pastures. When mixed with bromoxynil (Group C) or MCPA (Group I), they are used for broadleaf weed control in winter cereals.

2F.1 Mode of action and biochemical pathways

Group F herbicides block the production of carotenoids by inhibiting the enzyme phytoene desaturase.

Carotenoids play an important part in photosynthesis by capturing light energy and transferring it to the chlorophyll. Carotenoids also play three major protective roles in the photosynthetic apparatus. The first is to quench triplet chlorophyll molecules back to the ground state. The second is to quench singlet oxygen molecules back to the normal and non-destructive triplet state. The third is to moderate the photosystem reaction centres in very bright light.

If triplet chlorophyll is not moderated, it will produce reactive oxygen that destroys the photosynthetic apparatus within the thylakoid membrane. Destruction of chlorophyll leads to bleaching of the plant tissue.

Plants treated with Group F herbicides have lower levels of carotenoids; this allows the oxygen radicals to remove hydrogen from membrane fatty acids, producing a lipid radical. These lipid radicals interact with molecular oxygen to form peroxidised and other lipid radicals. This creates a self-sustaining chain reaction of lipid peroxidation that destroys chlorophyll and membrane lipids. Proteins are also damaged. The destruction of integral membrane components leads to leaky membranes and rapid tissue desiccation.
Section 2F Herbicide Use

For detailed explanation, go to Plant and Soil Sciences e-Library: Inhibitors of carotenoid biosynthesis.

2F.2 Absorption into the plant

Group F herbicides are lipophilic and have low water solubility (Table 2). Pyridinecarboxamide herbicides are absorbed through the leaves of emerged plants and the roots and shoots of emerging seedlings. Diflufenican and picolinafen are absorbed through the leaves and have some soil residual activity. Absorption by susceptible species is thought to be faster than in tolerant species such as wheat. Group F herbicides are formulated as emulsifiable concentrates to aid mixing and foliar absorption.

Norflurazon is a soil-active pre-emergent herbicide and is absorbed into the roots by diffusion. It is a dry flowable formulation applied to bare soil or tank mixed with a knockdown herbicide.

Table 2: Environmental characteristics of Group F herbicides.

<table>
<thead>
<tr>
<th>Group F class</th>
<th>Active ingredient</th>
<th>Example trade name</th>
<th>Water solubility (mg/L)</th>
<th>Log K_{ow}</th>
<th>Soil persistence (half-life @ 20°C) (days)</th>
<th>Soil mobility (K_{oc}/K_{foc})</th>
<th>Volatility (Henry’s Law constant, 25°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyridazinones</td>
<td>Norflurazon</td>
<td>Zoliar®</td>
<td>34</td>
<td>2.45</td>
<td>225</td>
<td>700, moderate</td>
<td>Non-volatile</td>
</tr>
<tr>
<td>Pyridinecarboxamide</td>
<td>Diflufenican</td>
<td>Brodal®</td>
<td>0.05</td>
<td>4.2</td>
<td>315</td>
<td>1996, slight</td>
<td>Non-volatile</td>
</tr>
<tr>
<td></td>
<td>Picolinafen</td>
<td>Sniper®</td>
<td>0.05</td>
<td>5.43</td>
<td>31</td>
<td>28,300, non-mobile</td>
<td>Non-volatile</td>
</tr>
</tbody>
</table>

Log K_{ow} = ratio of herbicide that is soluble in octanol (organic solvent) v. water; it is a good indicator of the lipophilic or hydrophilic nature of a herbicide; the larger the log K_{ow} value the more lipophilic the herbicide; herbicides with values between –1 and 1 should move in the phloem following foliar application. K_{oc} > 1000, binds strongly to soil; <500, moves in water.

2F.3 Translocation within the plant

There is limited translocation from the leaves to other parts of the plant. Root uptake and translocation is via the xylem. Susceptible species also appear to have more rapid translocation within the plant.

2F.4 Symptoms

Symptoms on larger plants begin with bleaching of the new growth. This bleaching and yellowing spreads through the plant and turns to necrosis or browning. Susceptible weeds germinate but show immediate chlorosis followed by irregular patches of white and/or mauve–pink discoloration. The chlorosis spreads within the aerial growth and the plants become necrotic and die. Lentils and lupins often show transient yellow or white banding on the leaves.

Photo 2: Chlorosis from diflufenican in barley.

Photo: David Pfeiffer
Photo 3: Brodal residues on TT canola causing purpling and bleaching.
Photo: David Pfeiffer

Photo 4: Zoliar (norflurazon) effects on wheat.
Photo: Andrew Storrie
2F.4.1 Timeframe for symptoms and plant death

Rate of development of symptoms and subsequent damage and death depend on the plant species, herbicide dose, age and size of plant, and rate of plant growth. Symptoms begin about five–seven days post-application. Death occurs from as early as two weeks to four–eight weeks post-application.

2F.5 Crop selectivity

Selectivity appears to be a function of differential absorption and translocation between susceptible and tolerant species as well as size of plants when treated (i.e., effective dose received). In most instances, diflufenican and picolinafen are applied to pastures and crops once they have emerged. Pasture legumes should have at least three trifoliate leaves and pulse crops must be well established (see label critical comments) before these herbicides are applied. See Table 3 for details of uses of Group F herbicides.

Norflurazon lacks crop selectivity as a post-emergent herbicide.

Diflufenican and picolinafen are tank-mixed with either a Group C or Group I herbicide, or both, or are available in formulations with Group C or Group I herbicides (e.g. Jaguar®, Tigrex®, Paragon®), to broaden the weed-control spectrum in winter cereals.

Photo 5: Jaguar damage in wheat.

Photo: David Pfeiffer
Table 3: Differences in efficacy between Group F chemical classes.

<table>
<thead>
<tr>
<th>Group F class</th>
<th>Herbicide example</th>
<th>Crops</th>
<th>Weeds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyridazinones</td>
<td>Norflurazon</td>
<td>Asparagus, citrus, cotton, cotton fallow, grapes, nuts, pome fruit and stone fruit</td>
<td>Nutgrass (Cyperus spp.) and other grass and broadleaf weeds</td>
</tr>
<tr>
<td>Pyridinecarboxamide</td>
<td>Diflufenican</td>
<td>Clover-based pasture, lupins, field peas, lentils, oilseed poppy</td>
<td>Brassica weeds, prickly lettuce, pheasant’s eye; suppression of a range of broadleaf weeds</td>
</tr>
<tr>
<td></td>
<td>Picolinafen</td>
<td>Field peas, narrow-leafed lupins</td>
<td>Wild radish (R. raphanistrum), suppression of capeweed</td>
</tr>
</tbody>
</table>

2F.6 Effect of environmental conditions on activity

Because Group F herbicides are poorly translocated, they act as contact herbicides when applied after weed emergence. Absorption of these herbicides via the roots is important for effective control, so available soil moisture is one of the critical factors in determining the efficacy of these herbicides.

2F.6.1 Light
These herbicides are used in winter on small weeds; therefore, light will have little effect except that sunny conditions will speed the development of symptoms.

2F.6.2 Temperature
As temperature increases, the rate of photosynthesis increases, and this speeds the production of radicals within the photosynthetic system. Frosts and cold stress will reduce the effectiveness of these herbicides.

2F.6.3 Humidity
Plants growing in higher humidity have less epidermal wax on the leaf surface than plants growing in low humidity. These conditions will increase the amount of foliar-applied herbicide entering the plant.

2F.6.4 Soil moisture stress
Moisture-stressed plants have thicker cuticles, which will slow the absorption of foliar-applied Group F herbicides. Addition of certain adjuvants can assist herbicide absorption into the plant.

Adequate moisture is required in the surface soil to enable root absorption of norflurazon, diflufenican and picolinafen. Drying of the surface soil will reduce the level of weed control when using these herbicides.

If crops are moisture-stressed, the level of damage from these herbicides will increase dramatically because plants will not be able to metabolise the herbicides before they affect photosynthesis.

2F.6.5 Rainfall
The rain-fast period for foliar application of group F herbicides is four hours.
Rain within four hours of application could reduce foliar uptake; however, it is likely to improve root uptake as long as there is no major run-off or erosion.

2F.7  Spray application

Foliar-applied Group F herbicides require very good coverage, because these herbicides are effectively contact herbicides with little downward translocation. Labels recommend applying 50–100 litres per hectare but they do not mention spray quality.

Medium to coarse spray quality should be used, depending on the situation. Target coverage should be 10–15% as measured with water-sensitive paper.

If Group F herbicides are in a tank mix with a Group I herbicide, they must be applied as a coarse (or larger) spray quality.

Soil-applied herbicides require an even coverage; however, they can be applied in a coarse to extremely coarse spray quality. If tank-mixed with a knockdown herbicide, they should be applied in the relevant spray quality for that knockdown herbicide.

2F.7.1  Adjuvants

Adding adjuvants is generally not recommended. Read the label for recommended uses of adjuvants.

2F.7.2  Water quality

Water quality has little effect on Group F herbicides, provided it is within reasonable guidelines.

2F.8  Further reading


Herbicide Group G modes of action

The Group G Mode of Action (MoA) herbicides are another group affecting photosynthesis. They inhibit protoporphyrinogen oxidase (PPO or protox), resulting in a loss of chlorophyll and carotenoids and in leaky membranes, which allow cells and cell organelles to dry and disintegrate rapidly.

Photo 1: Peanuts showing a loss of chlorophyll and cells that have subsequently dried out from a Blazer (actifluorefen) application.

There are six chemical classes within the Group G MoA as shown in Table 1. These classes are different types of chemicals; however, they affect the same biochemical pathways in the plant. They are also classified as Group E by the global Herbicide Resistance Action Committee (HRAC) and Group 14 by the Weed Science Society of America (WSSA) (http://hrac.tsstaging.com/tools/classification-lookup).

Table 1: Herbicides included in Group G.

<table>
<thead>
<tr>
<th>Chemical class</th>
<th>Active ingredient</th>
<th>Product examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diphenyl ethers</td>
<td>Acifluorfen</td>
<td>Blazer®, Goal®, Rout® (PM)</td>
</tr>
<tr>
<td></td>
<td>Oxyfluorfen</td>
<td></td>
</tr>
<tr>
<td>N-phenylphthalimides</td>
<td>Flumioxazin</td>
<td>Valor®</td>
</tr>
<tr>
<td>Oxadiazoles</td>
<td>Oxadiargyl</td>
<td>No registered products</td>
</tr>
<tr>
<td></td>
<td>Oxadiazon</td>
<td>Ronstar®</td>
</tr>
<tr>
<td>Phenylpyrazoles</td>
<td>Pyraflufen</td>
<td>Ecopar®, Pyresta® (PM)</td>
</tr>
<tr>
<td>Pyrimidindiones</td>
<td>Butafenacil</td>
<td>Logran® B-Power® (PM)</td>
</tr>
<tr>
<td></td>
<td>Saflufenacil</td>
<td>Sharpen®</td>
</tr>
<tr>
<td>Triazolinones</td>
<td>Carfentrazone</td>
<td>Hammer®, Affinity® Plus (PM),</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aptitude® (PM), Broadway® (PM)</td>
</tr>
</tbody>
</table>

PM, Product contains more than one active constituent.

Because of their rapid desiccation of plant tissues, some of these herbicides are commonly used as ‘spikes’ added at lower rates to other knockdown herbicides to speed ‘brown-out’. Others can be used at higher rates as soil residual herbicides in plantations and horticulture.
Carfentrazone and acifluorfen are used as post-emergent herbicides in a range of crops to control broadleaf weeds. Carfentrazone is also formulated for application to water bodies to control aquatic weeds.

### 2G.1 Mode of action and biochemical pathways

Group G herbicides block PPO, which is an enzyme involved in biosynthesis of chlorophyll and heme (needed for electron transfer chains), catalysing the oxidation of protoporphyrinogen to protoporphyrin IX (Figure 1). This leads to the accumulation of protoporphyrinogen IX, the first light-absorbing chlorophyll precursor. This accumulated precursor, in the presence of sunlight, reacts with molecular oxygen to form oxygen radicals, which in turn produce lipid radicals, initiating a chain reaction of lipid oxidation. Lipids and proteins are attacked and oxidised, resulting in loss of chlorophyll and carotenoids and in leaky membranes. The leaky membranes mean that cells and cell organelles rapidly dry and disintegrate.

![Biosynthesis pathway affected by Group G herbicides.](image)

**Figure 1:** Biosynthesis pathway affected by Group G herbicides.

### 2G.2 Absorption into the plant

Group G herbicides are rapidly absorbed by the foliage of plants, whereas root absorption is variable. Oxyfluorfen is poorly absorbed via the roots, and saflufenacil is well absorbed.

Soil-applied herbicide is absorbed by the shoots of emerging seedlings, with some uptake via the roots depending on the herbicide.

### 2G.3 Translocation within the plant

Group G herbicides are largely considered contact herbicides, in that transport is limited owing to the rapid desiccation of plant foliage, although some species are well controlled even when spray coverage is suboptimal.

Herbicides such as saflufenacil are also absorbed by the roots. Once absorbed by the roots, saflufenacil is predominantly translocated in the xylem, with some movement in the phloem. Saflufenacil appears to have a higher level of translocation than most other Group G herbicides.
2G.4 Symptoms

Symptoms are rapid leaf bleaching, desiccation and browning (necrosis), which is often localised around the site of droplet contact if spray coverage is suboptimal. Sublethal rates of acifluorfen may cause a bronzing effect on young leaves. Droplet spray drift leads to flecking or bleached spots on the leaves. Symptoms of soil-absorbed herbicide show as rapid chlorosis of newly emerged cotyledons and first leaves followed by rapid necrosis.

Photo 2: Flecking or bleached spots due to Affinity (carfentrazone) on wheat.

Photo 3: Necrosis of navy bean leaves due to Blazer (acifluorfen).

Video: Ohio State University Weed Science. Time lapse of Group G (Group 14 WSSA) herbicide fomesafen sprayed on giant ragweed.
2G.4.1 Timeframe for symptoms and plant death

Rate of development of symptoms and subsequent damage and death depend on the plant species, herbicide dose, age and size of plant, and rate of plant growth. Symptoms can be observed within a few hours of post-emergence application. Plant death occurs from as early as two–four days after treatment.
2G.5 Crop selectivity

Rapid metabolism of the herbicide plays a major role in tolerance; susceptible species cannot metabolise these herbicides. In the case of post-emergent herbicides such as carfentrazone, the herbicide is rapidly metabolised by wheat, maize, soybeans and potatoes.

Butafenacil and oxyfluorfen are non-selective because they are very slowly metabolised by the plant, or not metabolised.

Crop selectivity is also controlled by lower levels of translocation in tolerant species, such as in the roots of maize plants. See Table 2 for details of uses of Group G herbicides.

Table 2: Differences in efficacy between Group G chemical classes.

<table>
<thead>
<tr>
<th>Group G class</th>
<th>Herbicide</th>
<th>Crops</th>
<th>Weeds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diphenyl ethers</td>
<td>Acifluorfen</td>
<td>Adzuki beans, mungbeans, peanuts, soybeans, green beans, seed crops of siratro and stylo</td>
<td>Post-emergent control of a range of broadleaf weeds up to eight true leaves; some grasses pre-emergence at high application rate</td>
</tr>
<tr>
<td></td>
<td>Oxyfluorfen</td>
<td>Brassicas (broccoli, cabbages, cauliflower), coffee, tree plantations, fruit orchards, nut trees, olive trees, Duboisia (corkwood tree), grapevines, pyrethrum, fallow, tobacco</td>
<td>Annual grasses and broadleaf weeds</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Spike for knockdown herbicides up to 4-leaf weeds</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>At high application rates acts as a residual herbicide</td>
</tr>
<tr>
<td>N-phenylphthalimides</td>
<td>Flumioxazin</td>
<td>Prior to sowing barley, chickpeas, faba beans, field peas, lentils, lupins, maize, mungbeans, oats, sorghum, soybeans, sunflowers and wheat</td>
<td>Rapid knockdown of a range of grass and broadleaf weeds as a knockdown spike</td>
</tr>
<tr>
<td>Oxadiazoles</td>
<td>Oxadiargyl</td>
<td>Currently not registered in Australia</td>
<td>Pre- and early post-emergent control of grasses and broadleaf weeds</td>
</tr>
<tr>
<td></td>
<td>Oxadiazon</td>
<td>Woody ornamental shrubs and trees in nurseries and turf</td>
<td>Pre-emergent control of a wide range of annual grasses and broadleaf weeds</td>
</tr>
<tr>
<td>Phenylpyrazole</td>
<td>Pyraflufen-ethyl</td>
<td>Pre-sowing knockdown when premixed with glyphosate</td>
<td>Spike added to glyphosate to speed brown-out of grasses and broadleaf weeds and to improve control of marshmallow and wild radish</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post-emergent control in wheat, barley, triticale, oats and clover pastures</td>
<td></td>
</tr>
<tr>
<td>Pyrimidindiones</td>
<td>Butafenacil</td>
<td>Premix with glyphosate or triasulfuron; with glyphosate prior to sowing cereals, to commence a fallow; with triasulfuron in wheat</td>
<td>Control in a range of annual grasses and broadleaf weeds</td>
</tr>
<tr>
<td></td>
<td>Saflufenacil</td>
<td>Annual crops and forestry plantations, fallows, established citrus, pome and almond orchards, around commercial, industrial, and agricultural buildings and yards; on established lucerne crops, and harvest-aid application in pulse crops</td>
<td>A range of broadleaf weeds including volunteer cotton, small-flowered mallow and fleabane, and grass weeds</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Also used as a tank-mix spike for knockdown herbicides</td>
</tr>
<tr>
<td>Triazolinones:</td>
<td>Carfentrazone</td>
<td>Winter cereals and pyrethrum</td>
<td>Post-emergent broadleaf control</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Spike with pre-sowing knockdown herbicide</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Aquatic weeds</td>
</tr>
</tbody>
</table>

Often these herbicides are tank-mixed with a knockdown herbicide for pre-emergent control, or carfentrazone and pyraflufen-ethyl are mixed with a phenoxy (Group I) herbicide for post-emergent control of broadleaf weeds in cereal crops.
2G.6 Effect of environmental conditions on activity

Various environmental characteristics of Group G herbicides are presented in Table 3.

2G.6.1 Light

Sunlight is essential for these herbicides to work effectively because they affect the plant’s photosynthetic system when applied post-emergence.

2G.6.2 Temperature

As temperature increases, the rate of uptake of herbicide increases provided respiration and photosynthesis are not limited by the conditions. However, the total amount of herbicide absorbed does not change.

Warmer temperatures promote plant respiration and photosynthesis, which speeds the action of Group G herbicides.

2G.6.3 Humidity

Low humidity reduces absorption. Relative humidity >65% is recommended for post-emergent applications.

2G.6.4 Soil moisture stress

Reduced photosynthesis and respiration will reduce the efficacy of Group G herbicides.

2G.6.5 Rainfall

Group G herbicides are rapidly absorbed by foliage and strongly absorbed by soil colloids and organic matter.

Saflufenacil has a one-hour rain-fast period. The post-emergent herbicides acifluorfen, carfentrazone and pyraflufen-ethyl have a six-hour rain-fast period.

<table>
<thead>
<tr>
<th>Group G class</th>
<th>Active ingredient</th>
<th>Example trade name</th>
<th>Water solubility (mg/L)</th>
<th>Log K&lt;sub&gt;ow&lt;/sub&gt;</th>
<th>Soil persistence (half-life @ 20°C) (days)</th>
<th>Soil mobility (K&lt;sub&gt;oc&lt;/sub&gt;/K&lt;sub&gt;foc&lt;/sub&gt;)</th>
<th>Drift potential (Henry’s Law constant, 25°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diphenyl ethers</td>
<td>Acifluorfen</td>
<td>Blazer®</td>
<td>250,000</td>
<td>1.18</td>
<td>54</td>
<td>113, moderate</td>
<td>Non-volatile</td>
</tr>
<tr>
<td></td>
<td>Oxyfluorfen</td>
<td>Goal®</td>
<td>0.12</td>
<td>4.86</td>
<td>73</td>
<td>7566, non-mobile</td>
<td>Volatile</td>
</tr>
<tr>
<td>N-phenylphthalamides</td>
<td>Flumioxazin</td>
<td>Valor®</td>
<td>0.79</td>
<td>2.55</td>
<td>18</td>
<td>889, moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Oxadiazoles</td>
<td>Oxadiargyl</td>
<td>No products registered</td>
<td>0.37</td>
<td>3.95</td>
<td>19</td>
<td>1915, moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>Oxadiazon</td>
<td>Ronstar®</td>
<td>0.57</td>
<td>5.33</td>
<td>165</td>
<td>3200, moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Phenylpyrazole</td>
<td>Pyraflufen</td>
<td>Ecopar®</td>
<td>1</td>
<td>4.87</td>
<td>7</td>
<td>1480, moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Pyrimidineones</td>
<td>Butafenacil</td>
<td>One constituent of Logran® B-Power®</td>
<td>10</td>
<td>3.2</td>
<td>1</td>
<td>365, moderate</td>
<td>Non-volatile</td>
</tr>
<tr>
<td></td>
<td>Saflufenacil</td>
<td>Sharpen®</td>
<td>2100</td>
<td>2.6</td>
<td>20</td>
<td>9–55, mobile</td>
<td>Non-volatile</td>
</tr>
<tr>
<td>Triazolinones</td>
<td>Carfentrazone-ethyl</td>
<td>Affinity® Force</td>
<td>29</td>
<td>3.7</td>
<td>0.5</td>
<td>886, slight</td>
<td>Non-volatile</td>
</tr>
</tbody>
</table>

Log K<sub>ow</sub> ratio of herbicide that is soluble in octanol (organic solvent) v. water. It is a good indicator of the lipophilic or hydrophilic nature of a herbicide: the larger the log K<sub>ow</sub> value the more lipophilic the herbicide; herbicides with values between –1 and 1 should move in the phloem following foliar application. K<sub>oc</sub>/K<sub>foc</sub> >1000, binds strongly to soil; <500, moves in water. Solubility will vary with temperature and to a lesser degree pH.

2G.7 Spray application

Group G herbicides have limited translocation because of their rapid action; therefore, post-emergent spray coverage must be 15% as measured on watersensitive paper.

Saflufenacil plus glyphosate and post-emergent herbicides mixed with a phenoxy (Group I) herbicide must be applied as a coarse spray quality or larger. This requires an application volume of 50–80 litres per hectare (depending on label) to obtain the level of coverage needed.

Older herbicides such as acifluorfen recommend an application volume of 100–300 litres per hectare.

2G.7.1 Adjuvants

The use of adjuvants with in-crop post-emergent Group G herbicides is not recommended, or there is a warning of increased crop damage. On the other hand, use of an adjuvant with knockdown herbicides is often recommended.

Read the label for specific recommendations.

2G.7.2 Water quality

Water quality is generally not an issue with Group G herbicides; however, water quality must be taken into account when tank-mixed with another product, which might be affected.

2G.8 Further reading


Herbicide Group H modes of action

The Group H Mode of Action (MoA) herbicides block carotenene synthesis by inhibiting the enzyme 4-hydroxyphenyl-pyruvate dioxygenase (HPPD). Symptoms include the bleaching of new growth.

Group H herbicides are also classified as Group 27 by the global Herbicide Resistance Action Committee (HRAC) and Group F2 by the Weed Science Society of America (WSSA) (http://hrac.tsstaging.com/tools/classification-lookup).

There are three chemical classes within the Group H MoA as shown in Table 1. These classes are different types of chemicals; however, they affect the same biochemical pathways in the plant. The triketone herbicide mesotrione is currently not registered for use in Australia.

<table>
<thead>
<tr>
<th>Chemical class</th>
<th>Active ingredient</th>
<th>Product examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isoxazoles</td>
<td>Isoxaflutole</td>
<td>Balance®</td>
</tr>
<tr>
<td>Pyrazoles</td>
<td>Benzofenap</td>
<td>Taipan®</td>
</tr>
<tr>
<td></td>
<td>Pyrasulfotole</td>
<td>Precept®, Velocity®</td>
</tr>
<tr>
<td>Triketone</td>
<td>Bicyclopyrone</td>
<td>Talinor®</td>
</tr>
<tr>
<td></td>
<td>Mesotrione (not registered in Australia)</td>
<td>Callisto®, Tenacity®</td>
</tr>
</tbody>
</table>


Isoxaflutole was first commercialised in 1998 and is used in fallow, chickpeas and sugarcane for the pre-emergent control of a range of annual grasses and broadleaf weeds. Benzofenap was first registered in Japan in 1981 and is now used in flooded rice in Australia. Pyrasulfotole was commercialised in Australia in 2009 and is formulated with either MCPA or bromoxynil to control a range of post-emergent broadleaf weeds in winter cereals.

Mesotrione is a mimic of the natural herbicide leptospermone, which is secreted by the crimson bottlebrush (Callistemon citrinus) and some other members of the myrtle family. It was commercialised in the northern hemisphere in 2001.

Bicyclopyrone was registered in 2015 and released in Australia in 2017 in a pre-mix with bromoxynil (Group C).

2H.1 Mode of action and biochemical pathways

Group H herbicides block the production of carotenoids by inhibiting the enzyme HPPD. This enzyme is essential for the production of plastoquinone, which is also a co-factor in the biosynthesis of carotene (Figure 1).

Carotenoids play an important part in photosynthesis by capturing light energy and transferring it to the chlorophyll. Carotenoids also play three protective major roles in the photosynthetic apparatus. The first role is to quench triplet chlorophyll molecules back to the ground state. The second is to quench singlet oxygen molecules back to the normal and non-destructive triplet state. The third is to moderate the photosystem reaction centres in bright light. If triplet chlorophyll is not moderated, it will produce reactive oxygen, which destroys the photosynthetic apparatus within the thylakoid membrane. Destruction of chlorophyll leads to bleaching of the plant tissue.

Plants treated with Group H herbicides have lower levels of carotenoids, allowing the oxygen radicals to remove hydrogen from membrane fatty acids, producing a lipid
radical. These lipid radicals interact with molecular oxygen to form peroxidised and other lipid radicals. This creates a chain reaction of lipid peroxidisation that destroys chlorophyll and membrane lipids. Proteins are also damaged. The destruction of integral membrane components leads to leaky membranes and rapid tissue desiccation.

For a detailed explanation go to: Plant & Soil Sciences eLibrary Lessons: Inhibitors of carotenoid biosynthesis.

Figure 1: Biosynthesis pathways affected by Group H herbicides.

2H.2 Absorption into the plant

Group H herbicides range in water solubility and tend to be lipophilic (Table 2). Isoxaflutole has low water solubility and is lipophilic, whereas its active form diketonitrile (DKN) is water-soluble and highly mobile in the plant. The greater lipophilicity of isoxaflutole gives greater uptake by seed, shoot and root tissues. DKN is formed rapidly in plants following uptake by the roots and shoots. Isoxaflutole also undergoes conversion to DKN in the soil.

Benzofenap is absorbed by roots and meristems of small plants.

Pyrasulfotole and bicyclopyrone are highly water-soluble. Once inside the plant, however, they are not well translocated within the phloem.
### Table 2: Environmental characteristics of Group H herbicides.

<table>
<thead>
<tr>
<th>Group H class</th>
<th>Active ingredient</th>
<th>Example trade name</th>
<th>Water solubility (mg/L)</th>
<th>Log K&lt;sub&gt;ow&lt;/sub&gt;</th>
<th>Soil persistence (half-life at 20°C) (days)</th>
<th>Soil mobility (K&lt;sub&gt;soil&lt;/sub&gt;/K&lt;sub&gt;foc&lt;/sub&gt;)</th>
<th>Volatility (Henry’s Law constant, 25°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isoxazoles</td>
<td>Isoxaflutole</td>
<td>Balance&lt;sup&gt;®&lt;/sup&gt;</td>
<td>6.2</td>
<td>2.34</td>
<td>0.5–3</td>
<td>145, low</td>
<td>Non-volatile</td>
</tr>
<tr>
<td></td>
<td>DKN (active molecule)</td>
<td>326</td>
<td>0.4</td>
<td>20–30</td>
<td>Moderate</td>
<td>Non-volatile</td>
<td></td>
</tr>
<tr>
<td>Pyrazoles</td>
<td>Benzofenap</td>
<td>Taipan&lt;sup&gt;®&lt;/sup&gt;</td>
<td>0.13</td>
<td>4.69</td>
<td>38</td>
<td>Immobile</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>Pyrasulfotole</td>
<td>Velocity&lt;sup&gt;®*&lt;/sup&gt;</td>
<td>69,100</td>
<td>–1.36</td>
<td>55</td>
<td>368, moderate</td>
<td>Non-volatile</td>
</tr>
<tr>
<td>Triketone</td>
<td>Bicyclopyrone</td>
<td>No products registered</td>
<td>119,000</td>
<td>?</td>
<td>213</td>
<td>Highly mobile</td>
<td>Non-volatile</td>
</tr>
<tr>
<td></td>
<td>Mesotrione</td>
<td>Callisto&lt;sup&gt;®&lt;/sup&gt; (no products registered in Australia)</td>
<td>1500</td>
<td>0.11</td>
<td>5</td>
<td>122, moderate</td>
<td>Non-volatile</td>
</tr>
</tbody>
</table>

Diketonitrile (DKN) is the active form of isoxaflutole. Log K<sub>ow</sub> ratio of herbicide that is soluble in octanol (organic solvent) v. water, it is a good indicator of the lipophilic or hydrophilic nature of a herbicide; the larger the log K<sub>ow</sub> value the more lipophilic the herbicide; herbicides with values between –1 and 1 should move in the phloem following foliar application. K<sub>soil</sub>/K<sub>foc</sub> >1000, binds strongly to soil; <500, moves in water.


#### 2H.3 Translocation within the plant

There is limited translocation from the leaves to other parts of the plant. Root uptake and translocation is via the xylem.

Without conversion to DKN, isoxaflutole would not be translocated within the plant. Translocation of benzofenap, pyrasulfotole and bicyclopyrone within the plant is limited.

#### 2H.4 Symptoms

Symptoms on larger plants begin with bleaching of the new growth. This bleaching and yellowing spreads through the plant, leading to necrosis (browning).

With soil-applied herbicide, susceptible weeds germinate and emerge but show immediate chlorosis followed by irregular patches of white and/or mauve–pink discoloration. The chlorosis spreads with the aerial growth and the plants become necrotic and die.
Photo 1: *Balance* (isoxaflutole) in faba beans causing yellowing and necrosis.

Photo: Andrew Storrie, Agromano

Photo 2: *Balance* (isoxaflutole) damage to chickpeas causing necrosis.

Photo: Kevin Moore NSW DPI
2H.4.1 Timeframe for symptoms and plant death

Rate of symptom development and subsequent damage and death depend on the plant species, herbicide dose, age and size of plant, and rate of plant growth. Death occurs from as early as two weeks to four to six weeks after treatment.

2H.5 Crop selectivity

Selectivity appears to be a function of speed of degradation in susceptible compared with tolerant species, as well as differences between varieties within a species, as well as separation of crop plants from treated soil (Table 3). In both plants and soil, the DKN is converted to the herbicidally inactive benzoic acid. This degradation is more rapid in maize than in susceptible weed species, and this contributes to the mechanism of selectivity, together with the greater sowing depth of the crop.

Photo: Kevin Moore, NSW DPI

Planting depth has been shown to influence the level of crop damage and is influenced by soil pH, clay content, organic matter, and time and intensity of rain after application.

Pyrasulfotole and bicyclopyrone have a safener added to the mix to speed degradation within crop plants.

Maize plants can rapidly metabolise bicyclopyrone into inactive compounds, and this contributes to the herbicide’s selectivity in killing weeds.
Table 3: Differences in efficacy between Group H chemical classes.

<table>
<thead>
<tr>
<th>Group H class</th>
<th>Herbicide example</th>
<th>Crops</th>
<th>Weeds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isoxazoles</td>
<td>Isoxaflutole</td>
<td>Sugarcane, chickpeas, fallow</td>
<td>All pre-emergent applications in Australia, except for sugarcane. Fleabane (<em>Conyza bonariensis</em>), sowthistle (<em>Sonchus oleraceus</em>), feathertop Rhodes grass (<em>Chloris virgata</em>), cape weed, <em>Crassula</em> spp., Indian hedge, mustard, medic, prickly lettuce, turnip weed and wild radish; suppression of <em>Echinochloa</em> spp., deadnettle, slender celery</td>
</tr>
<tr>
<td>Pyrazoles</td>
<td>Benzofenap</td>
<td>Rice</td>
<td>Arrowhead, <em>Alisma</em> spp., starfruit, water plantain; suppression of <em>Cyperus difformis</em></td>
</tr>
<tr>
<td>Pyrasulfotole</td>
<td></td>
<td>Wheat, barley, cereal rye and triticale; oats (Precept®)</td>
<td>Post-emergent control of broadleaf weeds</td>
</tr>
<tr>
<td>Triketone</td>
<td>Bicyclopyrone</td>
<td>Talinor®, registered in Wheat and Barley</td>
<td>Post-emergent control of broadleaf weeds</td>
</tr>
<tr>
<td></td>
<td>Mesotrione</td>
<td>Not registered in Australia</td>
<td>Pre-emergent control of annual grasses and broadleaf weeds</td>
</tr>
</tbody>
</table>

Pyrasulfotole and bicyclopyrone can be formulated with either a Group C or Group I herbicide, or both, to broaden the weed-control spectrum in grass crops.

### 2H.6 Effect of environmental conditions on activity

Because Group H herbicides are poorly translocated, they act as contact herbicides when applied following weed emergence. Absorption of these herbicides via the roots is important for effective control; therefore, available soil moisture is a critical factor in determining the efficacy of these herbicides.

#### 2H.6.1 Light

Light intensity will influence the speed of development of the symptoms. Pyrasulfotole is recommended to be applied at least one hour before sunset, particularly if followed by low night temperatures. Isoxaflutole is stable on the soil surface and not subject to photodegradation.

#### 2H.6.2 Temperature

As temperature increases, the rate of photosynthesis increases, which speeds the production of radicals within the photosynthetic system. Frosts and cold stress will reduce the effectiveness of these herbicides and can lead to increased crop damage.

#### 2H.6.3 Humidity

Plants growing in conditions of higher humidity have less epidermal wax on the leaf surface than plants growing in low humidity. These conditions will increase the amount of foliar-applied herbicide entering the plant.
2H.6.4 Soil moisture stress

Moisture-stressed plants have thicker cuticles, which will slow the absorption of foliar-applied Group H herbicides. Addition of certain adjuvants can assist herbicide absorption into the plant.

Adequate moisture is required at the surface soil to enable root absorption of isoxaflutole, its active form DKN, and pyrasulfotole. Drying of the surface soil will reduce the level of weed control when using these herbicides.

Isoxaflutole requires moisture at the soil surface, where it can be taken up by surface-germinating weed seeds to be converted to the more soluble DKN.

Benzofenap is applied to flooded rice bays, so the herbicide diffuses from the water into the weeds.

2H.6.5 Rainfall

The rain-fast period for foliar application of pyrasulfotole is two hours, suggesting rapid binding to cuticular waxes.

Rain is required to incorporate isoxaflutole into the surface soil.

Significant rain following application of bicyclopyrone application can lead to its movement down the profile into the root-zone.

2H.7 Spray application

Pyrasulfotole requires very good coverage because this herbicide is effectively a contact herbicide with little downward translocation. Labels recommend applying 50–150 litres per hectare for optimum coverage with medium quality.

Target coverage should be 10–15% as measured with water-sensitive paper.

Soil-applied herbicides need even coverage; however, they can be applied in a coarse to extremely coarse spray quality. If tank-mixed with a knockdown herbicide, they should be applied in the relevant spray quality for that knockdown herbicide.

2H.7.1 Adjuvants

Addition of adjuvants to isoxaflutole and benzofenap is not required because of their use pattern in Australia. Research in North America has shown improved post-emergent weed control when isoxaflutole is applied with a methylated seed oil adjuvant; however, this can increase crop phytotoxicity.

Pyrasulfotole requires crop oil adjuvant except when mixed with the grass herbicide Wildcat®, when a non-ionic surfactant is recommended.

2H.7.2 Water quality

Water quality has little effect on Group H herbicides, provided it is within reasonable quality parameters.

2H.8 Further reading


Herbicide Group I modes of action

The Group I Mode of Action (MoA) herbicides are synthetic plant hormones or auxins primarily targeting broadleaf (dicot) weeds, but some monocots as well.

They are also classified as Group O by the global Herbicide Resistance Action Committee (HRAC) and Group 4 by the Weed Science Society of America (WSSA) (http://hrac.tsstaging.com/tools/classification-lookup).

There are five chemical classes within the Group I MoA as shown in Table 1. These classes are different types of chemicals; however, they affect the same biochemical pathways in the plant.

Table 1: Herbicides included in Group I.

<table>
<thead>
<tr>
<th>Chemical class</th>
<th>Active ingredient</th>
<th>Product examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arylpicolinates</td>
<td>Halauxifen</td>
<td>Paradigm™ (PM), Kamba® M (PM)</td>
</tr>
<tr>
<td>Benzoic acids</td>
<td>Dicamba</td>
<td>Broadside® (PM), Kamba® M (PM)</td>
</tr>
<tr>
<td>Phenoxyacarboxylic</td>
<td>2,4-D</td>
<td>Amicide®, Estercide®</td>
</tr>
<tr>
<td>acids (phenoxys)</td>
<td>2,4-DB</td>
<td>Trifolamine®</td>
</tr>
<tr>
<td></td>
<td>Dichlorprop</td>
<td>Lantana 600</td>
</tr>
<tr>
<td></td>
<td>MCPA</td>
<td>MCPA, Agtryne® MA (PM), Buctril® MA (PM)</td>
</tr>
<tr>
<td></td>
<td>MCPB</td>
<td>Nufarm MCPB-400</td>
</tr>
<tr>
<td></td>
<td>Mecoprop</td>
<td>Methar Tri-Kombi® (PM)</td>
</tr>
<tr>
<td>Pyridine carboxylic</td>
<td>Aminopyralid</td>
<td>FallowBoss™ Tordon™ (PM), ForageMax™ (PM), Grazon® Extra (PM), Hotshot™ (PM), Vigilant™ II (PM)</td>
</tr>
<tr>
<td>acids (pyridines)</td>
<td>Clopyralid</td>
<td>Lontrel®, Spearhead® (PM)</td>
</tr>
<tr>
<td></td>
<td>Fluroxypyr</td>
<td>Starane®, Hotshot™ (PM)</td>
</tr>
<tr>
<td></td>
<td>Picloram</td>
<td>Tordon™ 75-D (PM), FallowBoss™ Tordon™ (PM), Grazon® Extra (PM)</td>
</tr>
<tr>
<td></td>
<td>Triclopyr</td>
<td>Garlon™</td>
</tr>
<tr>
<td>Quinoline carboxylic</td>
<td>Quinclorac</td>
<td>Drive®</td>
</tr>
<tr>
<td>acids</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

PM: Product contains more than one active constituent.


The Group I herbicide 2,4-D was commercially released after World War II and was the first of the ‘new’ synthetic herbicides that have been the basis of weed-control practices for the last 70 years.

Global use of Group I herbicides is an estimated 200 million hectares annually. They are used as post-emergent herbicides in a wide range of crops, as well as for fallow and non-agricultural weed control. Some have soil residual properties.

21.1 Mode of action and biochemical pathways

Group I herbicides are synthetic plant hormones (auxins) and mimic the key plant hormone indole-3-acetic acid (IAA). These herbicides are less prone to degradation or inactivation than the natural hormone and cause increased activity of the auxin-responsive genes, particularly those producing abscisic acid and ethylene. This leads to unregulated plant cell growth then to distortion of growing parts, growth inhibition,
senescence and tissue decay in sensitive broadleaf plants (dicots) and a small range of monocots (grass-like plants) such as sedges.

The production of high levels of ethylene and the reduction in photosynthesis resulting from stomatal closure by abscisic acid leads to the formation of high levels of reactive oxygen molecules, which in turn cause tissue deformation and twisting (epinasty).

One chemical class—the quinoline carboxylic acids—also has activity on some grasses as well as broadleaf weeds. In sensitive grasses, there is a rapid increase in ethylene, carbon dioxide and nitrates plus an accumulation of cyanide in the plant tissues.

For a detailed explanation, go to Plant & Soil Science eLibrary: Auxin and auxinic herbicide mechanism(s) of action.

21.2 Absorption into the plant

Most Group I herbicides such as 2,4-D are formulated as ‘pro-herbicides’ to enable better absorption by the plant because the active acid forms have low solubility in water. Therefore, they are formulated either as a salt (sodium, potassium, amine or choline) or as an ester to improve movement into the plant. Quinclorac is the exception and is formulated as an acid.

The different formulations are converted to the active acid form once inside the plant.

Group I herbicides can be absorbed through leaves, stems and shoots as well as roots.

Salt formulations are water-soluble (Table 2), meaning that they move through the cuticle and epidermis via the ‘aqueous route’, which is like the holes in a sponge. This route into the leaf tends to be relatively slow. For salt (polar) formulations to enter the leaf, they must remain dissolved in the water droplet. When the water has evaporated from the droplet, a crystalline deposit remains and movement into the leaf stops until it can be re-wet by high humidity, dew or light rain.

Ester formulations, which are lipophilic (fat loving), rapidly absorb into the cuticular waxes on the leaf surface and move to the leaf epidermis via diffusion. Initial absorption is very fast, making ester formulations less affected by water quality and environmental conditions.

Salt formulations of these herbicides are readily absorbed by plant roots.
The herbicide quinclorac is also absorbed from the soil through the coleoptiles of emerging grasses.

### Table 2: Environmental characteristics of Group I herbicides.

<table>
<thead>
<tr>
<th>Group I class</th>
<th>Active ingredient</th>
<th>Example trade name</th>
<th>Water solubility (mg/L)</th>
<th>Log $K_{ow}$</th>
<th>Soil persistence (half-life @ 20°C) (days)</th>
<th>Soil mobility ($K_{oc}/K_{foc}$)</th>
<th>Drift potential (Henry’s Law constant, 25°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arylpicolinates</td>
<td>halaxifen methyl</td>
<td>Arylex®</td>
<td>1.83</td>
<td>3.76</td>
<td>1.3 (1 – 2)</td>
<td>995 (190 – 1812)</td>
<td>1.5 x 10^6</td>
</tr>
<tr>
<td>Benzoic acids</td>
<td>Dicamba (DMA)</td>
<td>One constituent of Broadside®</td>
<td>250,000, high</td>
<td>0.29</td>
<td>4 (3–5)</td>
<td>12.4, very mobile</td>
<td>Non-volatile</td>
</tr>
<tr>
<td>Phenoxys</td>
<td>2,4-D</td>
<td>Amicide®</td>
<td>24,300, high</td>
<td>2.81</td>
<td>29 (22–38)</td>
<td>0.7, very mobile</td>
<td>Non-volatile</td>
</tr>
<tr>
<td></td>
<td>2,4-DB</td>
<td>Triflamine®</td>
<td>4,385, high</td>
<td>1.22</td>
<td>16 (7–24)</td>
<td>500, moderate</td>
<td>Non-volatile</td>
</tr>
<tr>
<td></td>
<td>MCPA</td>
<td>MCPA</td>
<td>29,390, high</td>
<td>–0.81</td>
<td>25 (7–41)</td>
<td>110, mobile</td>
<td>Non-volatile</td>
</tr>
<tr>
<td>Pyridines</td>
<td>Aminopyralid</td>
<td>Hotshot®</td>
<td>2480, high</td>
<td>–2.87</td>
<td>21 (8–35)</td>
<td>8.3, very mobile</td>
<td>Non-volatile</td>
</tr>
<tr>
<td></td>
<td>Clopyralid</td>
<td>Lontrel®</td>
<td>143,000, high</td>
<td>–2.63</td>
<td>11 (2–24)</td>
<td>5, very mobile</td>
<td>Non-volatile</td>
</tr>
<tr>
<td></td>
<td>Fluoroxypr</td>
<td>Starane®</td>
<td>65,000, high</td>
<td>–1.5</td>
<td>51 (34–68)</td>
<td>68, mobile</td>
<td>Non-volatile</td>
</tr>
<tr>
<td></td>
<td>Triclopyr</td>
<td>Garlon®</td>
<td>1,000,000, high</td>
<td>4.62</td>
<td>30 (7–54)</td>
<td>27, mobile</td>
<td>Non-volatile</td>
</tr>
<tr>
<td></td>
<td>Picroxan</td>
<td>Tordon®</td>
<td>560</td>
<td>1.4</td>
<td>36 (20–49)</td>
<td>13, very mobile</td>
<td>Non-volatile</td>
</tr>
<tr>
<td>Quinolones</td>
<td>Quinclorac</td>
<td>Drive®</td>
<td>0.065, low</td>
<td>0.07</td>
<td>50, mobile</td>
<td>Non-volatile</td>
<td>Non-volatile</td>
</tr>
</tbody>
</table>

Log $K_{oc}$ ratio of herbicide that is soluble in octanol (organic solvent) v. water. It is a good indicator of the lipophilic or hydrophilic nature of a herbicide; the larger the log $K_{oc}$ value the more lipophilic the herbicide; herbicides with values between –1 and 1 should move in the phloem following foliar application. $K_{oc}/K_{foc}$ >1000, binds strongly to soil; <500, moves in water. Different formulations of each herbicide, such as the acid, salt and ester forms, will have different chemical and therefore environmental, compatibility and behaviour characteristics. Solubility will vary with temperature and to a lesser degree pH.

21.3 Vapour drift risk

Vapour drift risk is affected by a complex series of interactions including:

- molecular weight of herbicide
- herbicide formulation: acid < sodium salt < amine salt < ester
- amount of herbicide applied per hectare and total area treated
- tank mix partners such as ammonium sulfate
- meteorological conditions: air and soil temperature, humidity, wetting–drying of plants and soil, temperature inversions trapping herbicide vapour
- characteristics of surfaces where droplets or deposits land: soil, stubble, plant leaves (varies with species)
- size of droplets or deposits
- sensitivity of neighbouring crops and vegetation such as cotton, tomatoes, grape vines.

For most situations, vapour drift following herbicide application is a minor risk compared with droplet and particle drift during herbicide application. An analysis of the hazards and risks to neighbouring crops and sensitive areas should be conducted before spraying any herbicides.

21.4 Translocation within the plant

Group I herbicides have great mobility within the plant because they are intermediate in their hydrophilic and hydrophobic properties, allowing them to move through oily cell membranes and watery cytoplasm. This permits them to move both upward to the leaves and growing points and downward toward the roots of the plant.

They move rapidly through the cytoplasm of plant cells (the symplastic system) including the phloem. With root uptake, these herbicides follow the transpiration pathway, primarily within the sap within cell walls and spaces between the cells (the apoplast) (Figure 1). (For definitions of symplastic and apoplastic movement, see Herbicide GrowNotes: Group A)

Rapid absorption and translocation mean that cultivation or crop planting can occur within 24 hours of application with minimal effects on herbicide efficacy.

Figure 1: The path for root uptake.
Source: Biologyforums.com

21.5 Cellular absorption: passive diffusion and active absorption

The most common type of cellular absorption is passive, whereby the herbicide moves from an area of higher concentration (symplast) to an area of lower concentration in the cell.
The herbicide 2,4-D can also be absorbed into plant cells via active absorption, which moves the herbicide molecule across the cell membrane against the concentration gradient. This process increases the concentration of herbicide within the cell and it is facilitated by a protein carrier located in the cell membrane. For a detailed explanation of this process, go to Plant & Soil Science eLibrary: Cellular absorption of herbicides—active absorption.

Once inside the living plant tissue, the herbicides move inside the phloem with sugars and amino acids towards areas of growth and/or storage. These herbicides then accumulate in the growing tips of roots and shoots (meristems) where they interrupt growth.

Group I herbicides are also weak acids. Weak acids are compounds containing a functional group, usually a carboxylic acid. This functional group gains or loses a hydrogen ion depending on the pH of the surrounding solution (for more details, see Herbicide GrowNotes: Group A).

### 21.6 Symptoms

Symptoms are first exhibited and most severe on the new growth. Symptoms exhibited in dicot species include bending and twisting of young stems and petioles, swelling of stems and nodes, leaf cupping and curling. The area of newly forming leaves is restricted, with them becoming narrow and strap-like.

Growth slows, with growing points yellowing followed by wilting and death. Older growth reddens.

The herbicide quinclorac is also active on several grass species. Symptoms on grasses include cessation of growth with increased yellowing of the youngest leaves followed by wilting and browning of the entire shoot.

![Photo 3: Twisted canola stems from 2,4-D.](Photo: David Pfeiffer)
**Photo 4:** The effects of 2,4-D on wheat heads.

*Photo: Tony Cook*

**Photo 5:** Tordon damage in mungbeans.

*Photo: DPI&F*
Photo 6: Chickpeas with twisting and deformity from phenoxy.
Photo: Kevin Moore, NSW DPI

Photo 7: Picloram (Tordon) residues in faba beans.
Photo: Rohan Brill, NSW DPI
21.6.1 Timeframe for symptoms and plant death

Rate of development of symptoms and subsequent damage and death depend on the plant species, herbicide dose, age and size of plant, and rate of plant growth. Death occurs from as early as two weeks to around four–six weeks post-application:

- Within the first few hours of application is the stimulation phase. Production of ethylene increases, leading to twisting of new growth.
- After 24 hours, root and shoot growth stops and green pigmentation intensifies. Stomata close, leading to a reduction in transpiration and an increase in the concentration of reactive oxygen molecules. New growth becomes severely twisted.
- Chloroplasts within the cells are damaged and plant tissue progressively becomes more yellow. Cell membranes and the plant vascular system break down, leading to wilting and plant death.

21.7 Crop selectivity

Plants that are tolerant of Group I herbicides detoxify them by using P450 enzymes, which replace a chlorine group on the aromatic ring with a hydroxyl group. This then allows joining (conjugation) with glucose or other large molecules. Amino acids can also bind to a side chain of the herbicide molecule. These large molecules have no herbicidal activity and are then further broken down to carbon dioxide and other products.

Some plants that are not affected by Group I herbicides could also have receptor sites that do not allow binding of the herbicide molecule.

Because of differences in efficacy between the chemical classes (Table 3), they are often used as pre-mixes or tank mixes to broaden the number of species controlled. For example, the phenoxy MCPA is often combined with arylpicolinates, benzoic acids and pyridines to broaden the control spectrum.

Table 3: Differences in efficacy of Group I chemical classes according to plant family.

<table>
<thead>
<tr>
<th>Group I class</th>
<th>Dicot families</th>
<th>Non-grass monocots</th>
<th>Grasses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arylpicolinates</td>
<td>Boraginaceae, Fabaceae, Fumariaceae, Rubiaceae</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Benzoic acids</td>
<td>Amaranthaceae, Fabaceae, Polygonaceae</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NOT Brassicaceae</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phenoxyx</td>
<td>Amaranthaceae, Asteraceae, Boraginaceae, Chenopodiaceae, Cucurbitaceae, Geraniaceae, Lamiaceae, Polygonaceae, Rubiaceae, Solanaceae</td>
<td>Crassulaceae (e.g. stonecrop)</td>
<td>Cyperaceae (e.g. sedges)</td>
</tr>
<tr>
<td>Pyridines</td>
<td>Asteraceae, Fabaceae, Malvaceae, Rosaceae, Solanaceae</td>
<td>Cactaceae</td>
<td>Commelinaeaceae, Crassulaceae</td>
</tr>
</tbody>
</table>
2I.8 Effect of environmental conditions on activity

Water-soluble (hydrophilic) formulations (i.e. salts) will be more affected by environmental conditions than oil-soluble (lipophilic) formulations such as esters.

Herbicide effectiveness is influenced by the interaction of temperature, humidity and light intensity on the weed species, because this affects transpiration, respiration and leaf surface characteristics.

2I.8.1 Light

Conditions of high light intensity can thicken the cuticle of a weed, which will reduce the uptake of water-soluble formulations. Decreasing light intensity, such as occurs in autumn, increases the ratio of shoots to rhizomes in perennial species. This leads to better control through better herbicide interception and more herbicide translocating to the root system. There is also an increase in the amount of assimilates moving into roots and storage organs, which in-turn increases the transport of phloem-mobile herbicides, including those in Group I.

2I.8.2 Temperature

As temperature increases, the rate of uptake of herbicide increases provided respiration and photosynthesis are not limited by the conditions. However, the total amount of herbicide absorbed does not change. High temperatures and low available soil moisture reduce herbicide translocation through the shutdown of transpiration.

Optimum temperatures for photosynthesis and respiration are determined by whether the plants use C3 or C4 photosynthesis. C3 plants grow best at temperatures <30°C, whereas C4 plants can actively grow at temperatures up to 35°C and at higher light intensities.

Frost can shut down plant growth for several days and will reduce the translocation of Group I herbicides. Frost following the application of dicamba on oats causes the crop to lay flat on the ground. The crop usually recovers from this condition. Higher temperatures also increase the likelihood of vapour movement from treated areas. In the USA, herbicide companies have been looking at larger, stable molecules to reduce the potential of vapour drift and have released formulations of dicamba as diglycolamine and BAPMA (N,N-bis(aminopropyl)methylamine) salts and a choline formulation of 2,4-D.

2I.8.3 Humidity

Plants growing in conditions of higher humidity have less epidermal wax on the leaf surface than plants growing in low humidity. High humidity hydrates the cuticle, allowing for a continuous aqueous path to the epidermis for salt and amine formulations.

2I.8.4 Soil moisture stress

Stressed plants have thicker cuticles, which will absorb and hold more ester formulation herbicide, whereas amine and salt formulations will be prevented from penetrating a thick, dehydrated cuticle. Addition of certain adjuvants can assist
herbicide absorption into the plant; however, if it is not actively growing, translocation and efficacy will be limited.

### 2I.8.5 Rainfall

Both 2,4-D amine salt and ester formulation labels state a six-hour rain-fast period, dicamba sodium salt and dimethylamine salt labels suggest four hours, halaxifen methyl ester three hours, and fluroxypyr methylheptyl ester one hour. As previously noted, esters are rapidly absorbed into the waxy cuticle; however, the amount of cuticle will vary with weed species and growing conditions.

### 2I.9 Spray application

Group I herbicides are well translocated through the plant. However, all phenoxy herbicides MUST be applied as a coarse or larger quality to minimise the proportion of driftable (fine) droplets produced. For example, any mix that contains MCPA MUST be applied as a minimum coarse spray quality.

Pyridines are recommended to be applied as a medium to coarse droplet in most instances.

Although some labels of non-phenoxy classes such as dicamba and fluroxypyr do not recommend a spray quality, updated online information usually suggests coarse spray quality.

Application volumes can range from 50 to 250 litres per hectare for ground application, and all labels suggest a minimum of 50 litres per hectare.

Target coverage should be 6–15% as measured on water-sensitive paper.

### 2I.9.1 Adjuvants

Addition of adjuvants is rarely recommended with in-crop applications unless the Group I herbicide is being tank-mixed with a Group A herbicide. Adding extra adjuvant increases the chance of crop damage. Most herbicides will have a certain amount of adjuvant pre-mixed in the drum.

In a fallow or non-crop situation, most labels will recommend a non-ionic surfactant or oil, a non-ionic surfactant such as BS1000™ or a petroleum spray oil + emulsifier blend such as Uptake™. It is recommended that products containing halaxifen also be applied with either a non-ionic surfactant or a petroleum spray oil.

Read the label for recommended use of adjuvants.

The use of dicamba over the top of glyphosate + dicamba-resistant soybeans in the USA has shown that the volatility of dicamba increases significantly if ammonium sulfate is present in the tank mix.

### 2I.9.2 Water quality

#### Temperature

Recent research in the USA with a glyphosate + dicamba mix has shown that the control of certain species can be influenced by spray solution temperature. Warmer water (37°C compared with 5°C) gave 26% better control of pitted morning glory (*Ipomoea lacunosa*) and 14% better control of giant ragweed (*Ambrosia trifida*), but had no effect on control of flaxleaf fleabane (*Conyza bonariensis*) or Palmer amaranth (*Amaranthus palmeri*). Increasing the herbicide application rate reduced the temperature effect dramatically.

Low spray mix temperatures can greatly affect tank mixing. This will also depend on water quality, what products are being mixed and the quality of the products used.
pH
The effect of the pH of a spray solution is one of the most widely misunderstood concepts in spray application. The pH will have little effect on efficacy, although Group I herbicides are weak acids and perform slightly better (<5%) in a slightly acid solution. The addition of weak acid herbicides to a tank mix lowers the pH of the solution.

A decrease in the pH of a spray solution by using an unbuffered product such as citric acid can lead to chemicals coming out of suspension and gelling of the spray solution.

Hardness
Water hardness can significantly reduce the efficacy of amine, potassium and sodium salt formulations through the binding of larger cations of calcium and magnesium to the herbicide molecule, making them less soluble.

Research in the USA has shown that the effects of hard water on 2,4-D amine and dicamba are species-dependent, although dicamba was less affected than 2,4-D. Adding ammonium sulfate to the tank prior to 2,4-D improved control of fat hen (Chenopodium album), flaxleaf fleabane and redroot amaranth (Amaranthus retroflexus). Adding ammonium sulfate before dicamba improved control of fat hen and amaranth, but not fleabane.

Turbidity
Group I herbicides are generally not affected by the presence of clay and particulate matter in the spray solution; however, water of this quality should be treated to reduce blocking of filters and nozzles.

2I.10 Further reading


Herbicide Group J modes of action

The Group J Mode of Action (MoA) herbicides inhibit the synthesis of very-long-chain fatty acid lipids by a different mechanism from Group A herbicides. These fatty acids are necessary for the production of cuticular waxes, especially in the seedling stages of plants, and they affect cell elongation.

Group J is also classified as Group N by the global Herbicide Resistance Action Committee (HRAC) and Group 8 by the Weed Science Society of America (WSSA), although the WSSA rank the chlorocarbonic acids as a Group 26 (http://hrac.tsstaging.com/tools/classification-lookup).

Several of these herbicides were introduced to agriculture in the late 1950s. Many of these herbicides have been removed from use within the European Union because of environmental concerns, such as movement into the ground water, and some (e.g. bensulide) are Schedule 6 poisons.

There are four chemical classes within the Group J MoA as shown in Table 1. These classes are different types of chemicals, however, they affect the same biochemical pathways in the plant.

<table>
<thead>
<tr>
<th>Chemical class</th>
<th>Active ingredient</th>
<th>Product examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzofurans</td>
<td>Ethofumesate</td>
<td>Tramat®,</td>
</tr>
<tr>
<td>Chlorocarbonic acids</td>
<td>2,2-DPA</td>
<td>DalaPon</td>
</tr>
<tr>
<td></td>
<td>Flupropanate</td>
<td>Tussock®,</td>
</tr>
<tr>
<td>Phosphorodithioates</td>
<td>Bensulide</td>
<td>Exporsan®,</td>
</tr>
<tr>
<td>Thiocarbamates</td>
<td>EPTC</td>
<td>Eptam®,</td>
</tr>
<tr>
<td></td>
<td>Molinate</td>
<td>Ordram®,</td>
</tr>
<tr>
<td></td>
<td>Pebulate</td>
<td>Tillam®,</td>
</tr>
<tr>
<td></td>
<td>Prosulfocarb</td>
<td>Boxer Gold®,</td>
</tr>
<tr>
<td></td>
<td>Thiolbencarb</td>
<td>Saturn®</td>
</tr>
<tr>
<td></td>
<td>Triallate</td>
<td>Avadex®, Jetti Duo</td>
</tr>
<tr>
<td></td>
<td>Vernolate</td>
<td>No registered products</td>
</tr>
</tbody>
</table>

Boxer Gold® and Jetti Duo contain more than one active constituent.


The thiocarbamates and 2,2-DPA are the only Group J herbicides used in Australian broadacre agriculture.

Thiocarbamates are soil-applied herbicides used for pre-emergence control of annual grasses, sedges and annual broadleaf weeds (varies with herbicide). Usually, they are incorporated mechanically or with irrigation immediately after application to avoid vapour losses. Ethofumesate is used for pre- and post-emergent selective weed control in beet crops, oilseed poppies, onions and established turf. 2,2-DPA and flupropanate are used as post-emergent herbicides largely for the control of annual and perennial grasses and a range of other species. Flupropanate also has soil residual control of seedling grasses. These two herbicides were reintroduced into use with the spread of the difficult-to-control perennial grass weeds Sporobolus and Nassella spp.

In Australia, bensulide is used as a pre-emergent herbicide to control winter grass in established turf.
2J.1 Mode of action and biochemical pathways

Group J herbicides block several plant biochemical pathways including biosynthesis of fatty acids, proteins, isoprenoids and flavonoids, as well as inhibiting gibberellin synthesis. Photosynthesis may also be inhibited.

Thiocarbamates block an enzyme in fatty acid biosynthesis, stopping the formation of waxes and suberin, which are important in the formation of the waxy layer on the outside of seedlings and plants as well as in cell elongation.

For detailed explanation, go to Plant & Soil Sciences eLibrary: Inhibitors of fatty acid synthesis and elongation.

2J.2 Absorption into the plant

Group J herbicides are rapidly absorbed by roots and slowly translocated to shoots via the xylem.

Soil-applied herbicide is absorbed by the shoots of emerging seedlings, with some uptake via the roots, depending on the herbicide.

Thiocarbamates enter grass-weed seedlings through the coleoptile and the coleoptile node as it pushes through the treated layer of soil. Triallate can be absorbed by seedlings as a vapour at relatively low soil-moisture contents.

EPTC is absorbed through the hypocotyl hook of broadleaf seedlings. Prosulfocarb is absorbed through the leaves and the roots of seedlings.

2J.3 Translocation within the plant

Group J herbicides are rapidly absorbed by roots and shoots, with either very slow or little translocation from the roots to the shoots.

Translocation of thiocarbamates is limited but primarily occurs in the xylem, the rate being determined by water solubility of the herbicide. For example, EPTC is translocated more readily than triallate.

Both 2,2-DPA and fluopropanate are highly water-soluble (Table 2) and will move into the root-zone quickly with rain or irrigation. They are also tightly bound to organic matter.
### Table 2: Environmental characteristics of Group J herbicides.

<table>
<thead>
<tr>
<th>Group J class</th>
<th>Active ingredient</th>
<th>Example trade name</th>
<th>Water solubility (mg/L)</th>
<th>Log K&lt;sub&gt;ow&lt;/sub&gt;</th>
<th>Soil persistence (half-life @ 20°C) (days)</th>
<th>Soil mobility (K&lt;sub&gt;oc&lt;/sub&gt;/K&lt;sub&gt;foc&lt;/sub&gt;)</th>
<th>Drift potential (Henry’s Law constant, 25°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzoic acid</td>
<td>Ethofumesate</td>
<td>Tramat®</td>
<td>50</td>
<td>2.7</td>
<td>38</td>
<td>118, moderate</td>
<td>Non</td>
</tr>
<tr>
<td>Chlorocarbonic acid</td>
<td>2,2-DPA sodium</td>
<td>DalaPon</td>
<td>629,000</td>
<td>0.84</td>
<td>30</td>
<td>1, very mobile</td>
<td>Non</td>
</tr>
<tr>
<td>Fluoroacetate sodium</td>
<td>Tussock®</td>
<td></td>
<td>3,900,000</td>
<td>–1.9</td>
<td>365</td>
<td>8.7, very mobile</td>
<td>Non</td>
</tr>
<tr>
<td>Phosphonodithioates</td>
<td>Bensulide</td>
<td>Exporsan®</td>
<td>25</td>
<td>4.2</td>
<td>120</td>
<td>3,900, slight</td>
<td>Non</td>
</tr>
<tr>
<td>Thiocarbamates</td>
<td>EPTC</td>
<td>Eptom®</td>
<td>370</td>
<td>3.2</td>
<td>18</td>
<td>300, moderate</td>
<td>Non</td>
</tr>
<tr>
<td></td>
<td>Molinate</td>
<td>Ordram®</td>
<td>1,100</td>
<td>2.86</td>
<td>13</td>
<td>190, moderate</td>
<td>Non</td>
</tr>
<tr>
<td></td>
<td>Prosulfocarb</td>
<td>Boxer Gold®</td>
<td>13</td>
<td>4.48</td>
<td>10</td>
<td>1693, slight</td>
<td>Non</td>
</tr>
<tr>
<td></td>
<td>Thioebacarb</td>
<td>Saturn®</td>
<td>17</td>
<td>4.23</td>
<td>4</td>
<td>1062, slight</td>
<td>Non</td>
</tr>
<tr>
<td></td>
<td>Triallate</td>
<td>Avadex®</td>
<td>4</td>
<td>4.06</td>
<td>46</td>
<td>3034, slight</td>
<td>Moderate</td>
</tr>
<tr>
<td></td>
<td>Vernolate</td>
<td>No registered products</td>
<td>90</td>
<td>3.84</td>
<td>30</td>
<td>260, moderate</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

Log K<sub>ow</sub>, ratio of herbicide that is soluble in octanol (organic solvent) v. water. It is a good indicator of the lipophilic or hydrophilic nature of a herbicide, the larger the log K<sub>ow</sub> value the more lipophilic the herbicide. Herbicides with values between –1 and 1 should move in the phloem following foliar application. K<sub>oc</sub>/K<sub>foc</sub>: >1000, binds strongly to soil; <500, moves in water.


### 2J.4 Symptoms

With pre-emergent application, the seedlings usually fail to emerge from the soil. Cell elongation slows quickly. If shoots emerge, they are swollen and bright green. Shoots that emerge from the coleoptile can form a loop because they do not completely emerge.

Thiocarbamates tend to affect shoots more than roots. EPTC also reduces the deposition of cuticular waxes.
Photo 1: Black oat seedling affected by Avadex (triaxlate) resulting in a swollen bright green shot.

Photo: unknown
2J.4.1 Timeframe for symptoms and plant death

Rate of development of symptoms and subsequent damage and death depend on the plant species, herbicide dose, age and size of plant, and rate of plant growth.

With pre-emergent applications, weed seedlings will rarely emerge and die within two weeks. Depending on the effective dose, seedlings may keep growing and emerge as distorted plants after a couple of weeks.

Post-emergent applications of 2,2-DPA and flupropanate are very slow acting, and symptoms may not show for six weeks to several months for established perennial grasses and sedges.

2J.5 Crop selectivity

Selectivity is obtained with thiocarbamates by herbicide placement, usually in a treated zone above crop seeds with the physical separation of crop seed and seedlings from the herbicide-treated soil. Tolerant plants rapidly metabolise the herbicides, whereas susceptible plants activate the parent compound (some herbicides) so that it becomes herbicidally active (Table 3).
Table 3: Differences in efficacy between Group J chemical classes.

<table>
<thead>
<tr>
<th>Group J class</th>
<th>Herbicide</th>
<th>Crops</th>
<th>Weeds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzofurans</td>
<td>Ethofumesate</td>
<td>Beets, onions, oilseed poppies, turf</td>
<td>Pre- and post-emergent control of a range of annual grasses and broadleaf weeds</td>
</tr>
<tr>
<td>Chlorocarbonic acids</td>
<td>2,2-DPA</td>
<td>Range of permanent horticulture and non-crop areas, also sugarcane, cotton, potatoes, sunflower, maize, soybeans, tobacco</td>
<td>Non-selective control of annual and perennial grasses, sedges and cumbungi</td>
</tr>
<tr>
<td></td>
<td>Flupropanate</td>
<td>Non-crop areas, pastures, wooded areas</td>
<td>Perennial grasses such as <em>Sporobolus</em> spp. and <em>Nassella</em> spp.</td>
</tr>
<tr>
<td></td>
<td>Bensulide</td>
<td>Bowling and golf greens</td>
<td>Winter grass (<em>Poa annua</em>)</td>
</tr>
<tr>
<td>Thiocarbamates</td>
<td>EPTC</td>
<td>Beans, potatoes, maize, sweet corn, dryland safflower, dryland oilseed rape, furrow-sown sunflower, green beans, lucerne, <em>Duboisa</em>, <em>lotus</em>, non-crop areas</td>
<td>Pre-emergent control of a range of grass and broadleaf weeds</td>
</tr>
<tr>
<td></td>
<td>Molinate</td>
<td>Rice</td>
<td>Post-emergent control of annual grasses</td>
</tr>
<tr>
<td></td>
<td>Prosulfocarb</td>
<td>Wheat, barley, chickpeas, <em>Faba</em> beans, lentils, <em>field peas</em>, <em>lupins</em>, <em>potatoes</em></td>
<td>Annual ryegrass, <em>Vulpia</em> spp., <em>Crassula</em> spp., suppression of barley grass, and others</td>
</tr>
<tr>
<td></td>
<td>Thiobencarb</td>
<td>Rice (Amaroo variety only, aerial-sown into flooded bay)</td>
<td>Apply to dry soil and flood bays after application: barnyard grass and dirty Dora</td>
</tr>
<tr>
<td></td>
<td>Triallate</td>
<td>Wheat, barley, triticale, <em>canola</em>, <em>chickpeas</em>, <em>faba beans</em>, <em>lupins</em>, <em>field peas</em>, <em>linseed</em>, <em>safflower</em></td>
<td>Pre-emergent control of a range of annual grass and broadleaf weeds</td>
</tr>
</tbody>
</table>

Triallate is tank-mixed with trifluralin (and is available formulated with trifluralin as Jetti Duo) to broaden the weed-control spectrum. Prosulfocarb is pre-mixed with S-metolachlor (Group K) to broaden the spectrum and give more reliable control; the S-metolachlor is more water-soluble and helps incorporation with rainfall.

2J.6 Effect of environmental conditions on activity

These herbicides are lipophilic (see Table 3) and tend to be bound in soils with higher levels of organic matter.
They also tend to have low levels of water solubility, except for 2,2-DPA and flupropanate, so they tend to stay in the surface soil and need to be mechanically incorporated or moved in by irrigation or rainfall. Seedlings that germinate above the herbicide layer usually continue to grow.

Most Group J herbicides are degraded in the soil by microbes.

2J.6.1 Light
Photodegradation is not a major path of breakdown of these herbicides.

2J.6.2 Temperature
Temperature can affect the volatility of Group J herbicides when they are on the soil surface, particularly triallate.
Warmer soil temperatures promote plant growth, which speeds the action of Group J herbicides.

2J.6.3 Humidity
Humidity has little effect on the action of these herbicides.

2J.6.4 Soil moisture
Owing to the low solubility of these herbicides, adequate soil moisture is essential for absorption by seedlings and plant roots.
Although triallate is activated by low levels of soil moisture, there must be sufficient soil moisture for the weeds to germinate and grow for it to be affective.

2J.6.5 Rainfall
Despite triallate and prosulfocarb having lower levels of water solubility, rainfall will assist incorporation.

2J.7 Spray application
Group J herbicides have limited translocation because of their lipophilic characteristics. Triallate and prosulfocarb need to make contact with the soil, so should be applied as a coarse spray quality with an application volume that gives good crop residue penetration; for example, the Avadex® (triaiallate) label states 40–100 litres per hectare, and Boxer Gold® (prosulfocarb) a minimum of 50 but recommendation of 70 litres per hectare.
Large soil clods reduce the effective coverage of these herbicides and such situations should be avoided.

2J.7.1 Adjuvants
The only truly post-emergent herbicide in this group is 2,2-DPA, and it requires a non-ionic surfactant.

2J.7.2 Water quality
Water quality is generally not an issue with Group J herbicides. However, it must be taken into account when tank-mixing with another product because water quality may affect the tank-mix partner.
2J.8 Further reading


**Herbicide Group K modes of action**

The Group K Mode of Action (MoA) herbicides inhibit very-long-chain fatty acid (VLCFA) synthesis within the plastids (double-membrane organelles within cells), although the precise enzymatic steps are not known.

These herbicides are also classified as Group K by the global Herbicide Resistance Action Committee (HRAC) and as Group 15 by the Weed Science Society of America (WSSA) (http://hrac.tsstaging.com/tools/classification-lookup).

Group K herbicides were first commercially released in 1969, with alachlor. Several of these herbicides are now banned in the European Union owing to their potential to contaminate groundwater.

Chloroacetamides are widely used around the world, with metolachlor and S-metolachlor used in maize, sorghum and cotton, as well as nursery and landscape plantings and in turf. In North America, s-metolachlor can be applied through travelling irrigators and in liquid or dry bulk fertiliser.

Pyroxasulfone is the latest Group K herbicide to be released. In Australia, it is registered in bread wheat, triticale, chickpeas, field peas, lentils and lupins for the control of annual grasses and toad rush (*Juncus bufonius*). In North America, it is registered in maize, wheat and soybeans.

There are three chemical classes within the Group K MoA as shown in Table 1. These classes are different types of chemicals; however, they affect the same biochemical pathways in the plant.

<table>
<thead>
<tr>
<th>Chemical class</th>
<th>Active ingredient</th>
<th>Product examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetamides</td>
<td>Napropamide</td>
<td>Devrinol®</td>
</tr>
<tr>
<td>Chloroacetamides</td>
<td>Dimethenamid</td>
<td>Frontier-P®, Outlook®</td>
</tr>
<tr>
<td></td>
<td>Metolachlor/S-metolachlor</td>
<td>Dual Gold®, Boxer Gold®</td>
</tr>
<tr>
<td></td>
<td>Metazachlor</td>
<td>Butisan®, Cleranda® - metazachlor + imazamox (Gp B)</td>
</tr>
<tr>
<td></td>
<td>Propachlor</td>
<td>Ramrod®</td>
</tr>
<tr>
<td>Isoxazoline</td>
<td>Pyroxasulfone</td>
<td>Sakura®</td>
</tr>
</tbody>
</table>

Boxer Gold® contains more than one active constituent.


For more information on plastids, go to: [http://wwwbiologyexams4u.com/2012/06/plastids.html](http://wwwbiologyexams4u.com/2012/06/plastids.html)

**2K.1 Mode of action and biochemical pathways**

The primary target of the chloroacetamides has not been fully determined. Phytotoxic effects result from membrane disruption. Weeds are killed by severe growth inhibition of seedling shoot and root tissues soon after germination, apparently due to inhibition of cell elongation and cell division. It is also thought that germinating seedlings may not be able to utilise seed reserves. There is evidence that dimethenamid may act on a primary specific target in lipid metabolism. Establishment of seedlings is prevented.

Napropamide inhibits growth by blocking the progression of dividing cells through the cell cycle to mitosis. Reduced rates of cell division and DNA synthesis occur after treatment. This effect may be due to an inhibition in the synthesis or activity of
the cell-cycle-specific proteins. Alpha amylase activity is also inhibited, the extent of which is correlated with the inhibition of tuber germination and subsequent shoot growth in *Cyperus* spp.

Pyroxasulfone inhibits many elongation steps catalysed by the VLCFA elongases.

For detailed explanation, go to Plant & Soil Sciences eLibrary: Inhibitors of fatty acid synthesis and elongation.

### 2K.2 Absorption into the plant

Germinating grasses are more susceptible when the herbicide is absorbed by the shoot near the coleoptile node. Some herbicide will be absorbed by the roots. Broadleaf (dicot) species absorb chloroacetamides through shoots and roots.

### 2K.3 Translocation within the plant

Because chloroacetamide herbicides affect plant seedlings soon after germination, translocation is not an important biological property. They are lipophilic (Table 2), and phloem transport is unlikely.

Napropamide is rapidly translocated from the roots to the leaves in broadleaf words; however, there appears to be little movement from roots to shoots in grasses.

Despite pyroxasulfone being readily translocated from roots to shoots, it has no phytotoxic effect in established plants.

<table>
<thead>
<tr>
<th>Group K class</th>
<th>Active ingredient</th>
<th>Example trade name</th>
<th>Water solubility (mg/L)</th>
<th>Log $K_{ow}$</th>
<th>Soil persistence (half-life @ 20°C) (days)</th>
<th>Soil mobility ($K_m/K_{uw}$)</th>
<th>Drift potential (Henry’s Law constant, 25°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetamides</td>
<td>Napropamide</td>
<td>Devrinol®</td>
<td>74</td>
<td>3.3</td>
<td>72</td>
<td>839, slight</td>
<td>Non-volatile</td>
</tr>
<tr>
<td>Chloroacetamides</td>
<td>Dimethenamid-p</td>
<td>Outlook®, Frontier-P®</td>
<td>1499</td>
<td>1.89</td>
<td>7</td>
<td>227, moderate</td>
<td>Non-volatile</td>
</tr>
<tr>
<td>S-Metolachlor</td>
<td>Dual Gold®, Boxer Gold PM®</td>
<td>480</td>
<td>3.05</td>
<td>21</td>
<td>226, moderate</td>
<td>Moderate</td>
<td></td>
</tr>
<tr>
<td>Metazachlor</td>
<td>Butisan®</td>
<td></td>
<td>450</td>
<td>2.49</td>
<td>7</td>
<td>54, mobile</td>
<td>Volatile</td>
</tr>
<tr>
<td>Propachlor</td>
<td>Ramrod®</td>
<td></td>
<td>580</td>
<td>1.6</td>
<td>5</td>
<td>80, moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Isoxazoline</td>
<td>Pyroxasulfone</td>
<td>Sakura®</td>
<td>3.5</td>
<td>2.39</td>
<td>22</td>
<td>233, moderate</td>
<td>Non-volatile</td>
</tr>
</tbody>
</table>

Log $K_{uw}$ ratio of herbicide that is soluble in octanol (organic solvent) v. water. It is a good indicator of the lipophilic or hydrophilic nature of an herbicide. The larger the log $K_{uw}$ value, the more lipophilic the herbicide. Herbicides with values between –1 and 1 should move in the phloem following foliar application. $K_m/K_{uw}$ >1000 binds strongly to soil; <500, moves in water.


### 2K.4 Symptoms

With pre-emergent application, the seedlings usually fail to emerge from the soil. Cell elongation slows quickly. Susceptible monocots that do emerge appeared twisted and malformed with leaves tightly rolled in a whorl.

Broadleaf seedlings may have enlarged cotyledons, slightly cupped or crinkled leaves and shortened leaf midribs causing the leaf to look like the mid-vein has been drawn back towards the stem. Leaf colour can be very dark green.
Photo 1: Wheat damaged with Sakura on the right versus no damage on the left. Note the stunted and thickened coleoptiles, the majority of these plants will fail to emerge.

Photo: Penny Heuston

Photo 2: S-metolachlor causing sorghum leaves to tightly roll in a whorl.

Photo: Mark Congreve, ICAN
**2K.4.1 Timeframe for symptoms and plant death**

Rate of development of symptoms and subsequent damage and death depend on the plant species, herbicide dose, age and size of plant, and rate of plant growth.
2K.5 Crop selectivity

Selectivity of Group K herbicides is a combination of effects including physiological and positional selectivity (Table 3). Differential translocation between species also appears to play a role.

Selectivity of metolachlor and s-metolachlor in maize is due to the size of the germinating seed, position of seed in relation to the herbicide-treated soil, and the ability of the crop to metabolise the herbicide.

Maize cultivars can differ in sensitivity to acetamide herbicides. On light soils and particularly under adverse environmental conditions, phytotoxicity may occur if the herbicide moves into the crop seed zone.

Table 3: Differences in efficacy between Group K chemical classes.

<table>
<thead>
<tr>
<th>Group K class</th>
<th>Active ingredient</th>
<th>Crops</th>
<th>Weeds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetamides</td>
<td>Napropamide</td>
<td>Direct-seeded and transplanted tomatoes, almonds, stone fruit, grapevines</td>
<td>Pre-emergent control of a range of annual grasses and broadleaf weeds</td>
</tr>
<tr>
<td>Chloroacetamides</td>
<td>Dimethenamid-p</td>
<td>Field peas, lupins, chickpeas, green beans, navy beans, maize, sweet corn, kabocha squash, pumpkins</td>
<td>Pre-emergent control of a range of broadleaf and grass weeds</td>
</tr>
<tr>
<td>Metolachlor/ s-metolachlor</td>
<td>Broccoli, Brussels sprouts, cabbages, cauliflower, sorghum, soybeans, sunflowers, peanuts, maize, sweet corn, sugarcane, potatoes, sweet potatoes, green beans, navy beans, chickpeas, faba beans, field peas, lentils, lupins, tobacco, cotton, canola, wheat, barley, triticale, oats, clover pastures</td>
<td>Pre-emergent control of a wide range of grass and broadleaf weeds and toad rush</td>
<td></td>
</tr>
<tr>
<td>Propachlor</td>
<td>Maize, sweet corn, sorghum, direct-seeded onions; transplanted broccoli, Brussels sprouts, cabbages, cauliflower, Chinese cabbage; beetroot</td>
<td>Pre-emergent control of a range of grass and broadleaf weeds</td>
<td></td>
</tr>
<tr>
<td>Isoxazoline</td>
<td>Pyroxasulfone</td>
<td>Bread wheat, triticale, chickpeas, field peas, lentils, lupins</td>
<td>Pre-emergent control of a range of grass weeds and toad rush</td>
</tr>
</tbody>
</table>
2K.6 Effect of environmental conditions on activity

Group K herbicides are non-ionic and interact with soil organic matter (Figure 1). Metolachlor and s-metolachlor will bind approximately twice as much as pyroxasulfone.

Despite these herbicides having moderate leaching ability, several precautions need to be taken to ensure separation of crop seed from the herbicide.

The dimethenamid label states that it should not be used on soils with a low cation exchange capacity, clay content <10% or organic matter <2%.

S-Metolachlor should not be used on Brassica crops when the soil contains >60% sand and silt or is low in organic matter.

Group K herbicides are decomposed by microorganisms once within the soil.

Figure 1: Relationship between pyroxasulfone binding and organic matter in Australian soils. The higher the soil organic matter, the more the herbicide is bound.
Source: D Shaner 2013

2K.6.1 Light
Photodegradation is a major path of breakdown of metolachlor, s-metolachlor and napropamide when on the soil surface but plays only a minor role with dimethenamid and pyroxasulfone.

2K.6.2 Temperature
Warmer soil temperatures promote plant growth, which speeds the action of Group K herbicides. Warm, moist soil will also speed the decomposition of these herbicides.

Low soil temperatures will increase the likelihood of crop damage.

2K.6.3 Humidity
Humidity has little effect on the action of these herbicides.
2K.6.4 Soil moisture

Adequate soil moisture is required for Group K herbicides to make contact with roots and shoots via the soil solution and be absorbed. If weeds emerge through dry soil, they will be unaffected by these herbicides. Waterlogged conditions will increase the likelihood of crop damage.

2K.6.5 Rainfall

These herbicides require irrigation or rainfall to move into the top 50 mm of soil, or light cultivation such as incorporation by sowing. The pyroxasulfone label suggests incorporation within three days of spraying.

Leaching of these products into the crop seed zone is possible in soils of low clay and organic matter.

Group K herbicides intercepted by crop residue will need ~25 mm of rain to move 80% of the herbicide to the soil. S-Metolachlor and metolachlor will volatise from the crop residue.

2K.7 Spray application

Group K herbicides are effective only on germinating seedlings; therefore, even coverage of the soil is important. Even coverage of the soil is particularly important when spraying into crop residues.

These herbicides should be applied as a coarse spray quality with an application volume that gives good crop residue penetration; for example, the Sakura® (pyroxasulfone) label states 50–100 litres per hectare, and Dual Gold® (S-metolachlor) 60 litres per hectare.

Poor control is likely if applied to heavily rilled or excessively cloddy soil.

Pyroxasulfone also has a downwind buffer zone of 80 m where there are ponds, streams and rivers are present.

2K.7.1 Adjuvants

Because Group K herbicides are soil-active, adjuvants are unnecessary unless being tank-mixed with another product.

2K.7.2 Water quality

Water quality is generally not an issue with Group K herbicides. However, it must be taken into account when tank-mixing with another product because water quality may affect the tank-mix partner.

2K.8 Further reading


Herbicide Group L modes of action

The Group L Mode of Action (MoA) herbicides are also called bipyridyls and photosystem I (PSI) inhibitors. They are classified as Group D by the global Herbicide Resistance Action Committee (HRAC) and Group 22 by the Weed Science Society of America (WSSA) (http://hrac.tsstaging.com/tools/classification-lookup).

There are two herbicides within the Group L MoA: paraquat and diquat (Table 1). Both herbicides are active on grasses and dicot weeds; however, diquat is less effective on grasses.

Table 1: Herbicides included in Group L.

<table>
<thead>
<tr>
<th>Chemical class</th>
<th>Active ingredient</th>
<th>Product examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bipyridyls</td>
<td>Paraquat</td>
<td>Gramoxone®, Spray.Seed® (paraquat + diquat), Alliance® (amitrole + paraquat, pre-mix), Para-Trooper (paraquat + amitrole, pre-mix)</td>
</tr>
<tr>
<td></td>
<td>Diquat</td>
<td>Reglone®, Spray.Seed®</td>
</tr>
</tbody>
</table>

Paraquat was commercially released in 1960, with diquat released in 1962.

These herbicides are currently used on at least 140 million hectares globally and ~11 million hectares in Australia. In Australia, paraquat usage has increased dramatically since 2008 because it has been used as the second knock following glyphosate to manage the development of glyphosate resistance in fallows. There are >120 products on the Australian market containing paraquat. Many growers are now using paraquat as a knockdown herbicide in its own right because of the decline in price. Paraquat is also used for ‘spray-topping’, i.e. using a ‘normally sublethal rate’, to stop grass seedset selectively from clover pastures in spring and stop the seedset of weeds in pulses before harvest.

Diquat is largely used as a pre-harvest crop desiccant, a knockdown in lucerne and certain horticultural crops, and for weed control in aquatic areas.

2L.1 Mode of action and biochemical pathways

Group L herbicides block photosynthesis at the photosynthetic membrane system PSI, via electron diversion (see box text: What is photosystem I?). This process occurs within the chloroplasts.

2L.1.1 Diversion of electrons in photosystem I

Herbicides such as paraquat and diquat interact with the electron-transfer components associated with PSI. The paraquat ions have a strong positive charge and preferentially attract the free electrons produced by photosynthesis. When the herbicide is ‘reduced’ by an electron, it rapidly transfers the electron to oxygen, forming highly reactive superoxide including hydrogen peroxide. Chemically highly reactive, these superoxides attack unsaturated membrane fatty acids and chlorophyll, rapidly opening up and disintegrating the cell membranes and tissues. The paraquat acts as a catalyst and the ion--free radical process, then recycles producing further quantities of superoxide until the supply of free electrons ceases.
What is photosystem I (PSI)?

Photosystem I is the second part of the photosynthetic light reaction that occurs within the thylakoid membrane of the chloroplasts. Photosystem II uses light energy to oxidise two molecules of water into one molecule of molecular oxygen. The four electrons removed from the water molecules are transferred by an electron-transport chain through PSI, ultimately to reduce 2NADP⁺ to 2NADPH.

NADPH is a high-energy electron donor that is used in the Calvin–Benson cycle—the second stage of photosynthesis that takes place in the stroma of the chloroplasts—to reduce phosphoglycerate, producing phosphoglyceraldehyde. These aldehydes are used to create glucose.

The Calvin–Benson cycle can occur without sunlight.

2L.2 Absorption into the plant

Group L herbicides are highly water-soluble and polar (have a strong positive charge). They are rapidly absorbed by green plant tissues and are rain-fast within an hour. They are strongly absorbed to negative leaf surfaces.

A non-ionic surfactant is included in the formulation to ensure low surface tension of the solution and rapid movement through the aqueous pathway.

2L.3 Translocation within the plant

Group L herbicides are rapidly absorbed into the apoplast, including the xylem. They then enter plant cells via the active transport that moves the paraquat or diquat molecule across the cell membrane against its concentration gradient. This type of transport—called active absorption—involves a protein carrier located on the cell membrane that uses energy to move the herbicide from one side of the membrane to the other. The protein carries the molecule into the plant cell, increasing its concentration within the cell to levels well above those outside the cell. Paraquat is transported by the putrescine polyamine carrier.

In the presence of light, the herbicide is rapidly activated within the cells, causing massive damage to cell membranes. This rapid action prevents the translocation from treated leaves.

Application late in the day under low light conditions allows some movement within the xylem before the herbicide is activated by sunlight.

When soils are dry and relative humidity is high, downward movement of paraquat has been observed in potatoes, leading to tuber damage.

For more information on active absorption, go to Plant & Soil Sciences eLibrary: Cellular absorption of herbicides: Active absorption—three herbicide examples.

2L.4 Symptoms

Symptoms vary with plant type, herbicide rate, temperature and humidity.

Small weeds with good spray coverage will begin to wilt within a few hours of application, followed by complete desiccation in one to three days.

Larger plants and/or lower effective doses lead to wilting and interveinal yellowing within a few hours. Leaf edges brown first, followed by desiccation of the whole leaf.

At sublethal rates of herbicide, grasses can exhibit bleaching of new growth with death of older growth. This can be confused with damage from other herbicide MoAs.
Spray drift gives necrotic (brown) spotting on leaves.

YouTube video. Ohio State University Weed Science time lapse of effect of paraquat on giant ragweed.

### 2L.4.1 Timeframe for symptoms and plant death

Rate of development of symptoms and subsequent damage and death depend on the plant species, herbicide dose, age and size of plant, and rate of plant growth. Death occurs from as early as one day to six days after treatment.

### 2L.5 Plant selectivity

Despite plants being unable to metabolise paraquat and diquat, there are species differences in efficacy between herbicides. Translocation through the plant is limited by rapid action in the presence of light.

Paraquat is effective on a wide range of species but not effective on capeweed (*Arctotheca calendula*), black bindweed (*Fallopia convolvulus*) and *Erodium* species.

For effective control, grasses must be at least at the Z12 development stage on the Zadoks scale.

Established perennial species will regrow following spraying.

### 2L.6 Soil activity

Bipyridyl herbicides are irreversibly bound to clay particles and humus, owing to the strong positive charges on the cation. This makes them unavailable for microbial breakdown or leaching (Table 2).

**Table 2: Environmental characteristics of Group L herbicides.**

<table>
<thead>
<tr>
<th>Active ingredient</th>
<th>Example trade name</th>
<th>Water solubility (mg/L)</th>
<th>Log Kow</th>
<th>Persistence in soil (half-life @ 20°C) (years)</th>
<th>Soil mobility (Koc/Kfoc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paraquat dichloride</td>
<td>Gramoxone®</td>
<td>620,000</td>
<td>-4.5</td>
<td>20</td>
<td>Non-mobile</td>
</tr>
<tr>
<td>Diquat dibromide</td>
<td>Reglone®</td>
<td>718,000</td>
<td>-4.6</td>
<td>1–20</td>
<td>Non-mobile</td>
</tr>
</tbody>
</table>

Log Kow, ratio of herbicide that is soluble in octanol (organic solvent) v. water; it is a good indicator of the lipophilic or hydrophilic nature of a herbicide; the larger the log Kow value the more lipophilic the herbicide; herbicides with values between -1 and 1 should move in the phloem following foliar application. Koc/Kfoc >1000 binds strongly to soil, <500 moves in water.

### 2L.7 Effect of environmental conditions on activity

These herbicides are strongly absorbed by clay colloids. Foliar absorption by the plant is extremely rapid.

#### 2L.7.1 Light

Bipyridyl herbicides are activated by light through the generation of free electrons from photosynthesis.

Application of bipyridyls late in the day has shown modest improvements in herbicide efficacy by allowing more time for translocation within the plant.

In a trial in the USA, desiccation of cotton at days 3 and 14 after treatment was much better from evening applications than from morning and midday applications.

Failed maize stands were better controlled when a paraquat + Group C herbicide mix was applied at sunset than at sunrise.
In Australia, a trial comparing night and day paraquat applications for control of large awnless barnyard grass in fallow found that three litres per hectare (L/ha) applied at night was equivalent to 6 L/ha during the day (Table 3).

**Table 3: Effect of a single application of paraquat on large awnless barnyard grass plants (BYG) at day 24 after treatment.**

<table>
<thead>
<tr>
<th>Paraquat treatment</th>
<th>BYG alive per plot (2 m × 10 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Day</td>
</tr>
<tr>
<td>Untreated</td>
<td>210</td>
</tr>
<tr>
<td>2 L/ha</td>
<td>46</td>
</tr>
<tr>
<td>3 L/ha</td>
<td>59</td>
</tr>
<tr>
<td>6 L/ha</td>
<td>12</td>
</tr>
</tbody>
</table>

Source: Cook et al. 2015

Some photodegradation takes place on desiccated leaf surfaces and surface soil. This is estimated at 25–50% of the total applied over three weeks of strong light, but has not been unequivocally determined in the field.

2L.7.2 Temperature

As temperature increases, the rate of uptake of herbicide increases provided respiration and photosynthesis are not limited by the conditions. However, the total amount of herbicide absorbed does not change.

Higher temperatures increase the rate of photosynthesis; therefore, a greater quantity of reactive oxides will be produced, shortening the time for symptoms to develop.

2L.7.3 Humidity

High humidity increases the lifespan of hydrated droplets of Group L herbicides on the leaf surface. High humidity also makes the aqueous pathway through the cuticle more permeable to polar herbicides such as the bipyridyls.

Plants growing under high humidity also have thinner cuticles and are generally easier to control.

As noted previously, high humidity along with low soil moisture increases the downward movement of paraquat from the leaves to the tubers of potatoes during pre-harvest desiccation.

2L.7.4 Soil moisture stress

Stressed plants have thicker cuticles, which will increase the length of the aqueous path accessed by Group L herbicides. The additional waxes or hairs can increase herbicide runoff and droplet bounce, reducing herbicide coverage.

Moisture stress means lower rates of photosynthesis; therefore, fewer free electrons will be available for oxygen radicals.

2L.7.5 Rainfall

Group L herbicides are rain-fast anywhere between 15 minutes and two hours. Therefore, rain following application will have little effect on application.

2L.8 Spray application

Group L herbicides are poorly translocated within the plant because of their rapid action, so spray coverage is critical. Spray target should be at least 15% coverage.
Label recommendations vary from specifying a minimum application volume of 50 L/ha to 100–150 L/ha. Most Australian growers will now have a minimum application volume of 70 L/ha.

No spray-quality recommendation is listed on labels. Generally, however, a medium to coarse spray quality would be recommended, with increasing application volume as spray quality becomes coarser.

2L.8.1 Adjuvants

Additional wetting agents are not required with lower concentration products (e.g. 250 g/L) unless high-volume spraying results in excessive dilution of the wetter (i.e. <400 mL per 100 L spray volume) or for the control of certain species.

Higher concentration products such as Gramoxone® 360 always require additional adjuvant because there is less in the formulation.

Read the label for recommended use of adjuvants.

2L.8.2 Water quality

Bipyridyl herbicides are not affected by most of the water-quality problems that affect weak acid herbicides.

Temperature

No data is available on the effect of low spray-solution temperatures on efficacy.

pH

Bipyridyl herbicides are stable in acid–neutral pH solutions but unstable in alkaline solutions.

Do not leave spray mixed overnight.

Hardness

Hardness has no effect on bipyridyl herbicides.

Turbidity

Water containing clay, silt or algae is unsuitable for using with bipyridyl herbicides. These herbicides bind tightly to soil particles and organic matter.

Water that has contains these impurities should be stored in settling tanks and filtered before use.

Low levels of turbidity can be overcome by using higher label rates and the lower end of application volumes.

2L.9 References


Shaner DL (2014) 'Herbicide handbook.' (Weed Science Society of America: Lawrence, KS, USA)

Herbicide Group M modes of action

The Group M Mode of Action (MoA) herbicides are glycines and are represented by the single herbicide glyphosate. Glyphosate is classified as Group G by the global Herbicide Resistance Action Committee (HRAC) and Group 9 by the Weed Science Society of America (WSSA) (http://hrac.tsstaging.com/tools/classification-lookup).

Glyphosate is a non-selective herbicide, active against most grass, other monocot (e.g. sedges and lilies) and dicot species, although it is most effective on grasses.

Glyphosate is the most widely used herbicide in the world, with annual global sales of more than $6 billion, exceeding the combined sales of the next 10 most used crop-protection products. To allow over-the-top crop spraying of glyphosate, resistance genes have been introduced to cultivars of maize, soybean, cotton, lucerne, canola, sugar beet, tobacco, tomato, chicory, carrots and petunias.

2M.1 Biochemical pathway

Glyphosate blocks the shikimate biosynthetic pathway by binding to 5-enolpyruvyl-shikimate-3-phosphate (EPSP) synthase (Figure 1). The shikimate pathway produces the three key aromatic amino acids tryptophan, tyrosine and phenylalanine, which are essential for the production of auxins, phytoalexins, folic acid, lignin, plastoquinones and other secondary products required to fix carbon for plant growth. 1

Figure 1: The shikimate pathway.

Blocking the shikimate pathway leads to a reduction in sugar production and a buildup of toxic products such as shikimate. 2

The shikimate pathway occurs in the chloroplasts in the leaves and, importantly, in the meristematic regions of the plant (tips of roots, shoots and cambium) where cell

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division is occurring. After absorption, glyphosate translocates to these meristematic regions, to which the products of photosynthesis are also moved (carbon sinks).

The shikimate pathway occurs in plants, fungi, bacteria and many other single celled organisms but not in animals; hence, glyphosate has low toxicity to vertebrate and invertebrate animal species.

2M.2 Absorption into the plant

Glyphosate penetrates the leaf through the spaces in the leaf cuticle (aqueous pathway) then the epidermis by diffusion. The rate of penetration is determined by herbicide formulation, herbicide rate (concentration of herbicide in droplet), adjuvants and environmental conditions.

Water solubility of glyphosate is affected by the pH of the solution, temperature and formulation (Table 1). Glyphosate acid has a relatively low water solubility. To improve its uptake by increasing its solubility, it is formulated as a salt (isopropylamine, di-ammonium, mono-ammonium or potassium).

When formulated as a salt, glyphosate is able to enter the leaf via the cuticle and epidermis quite easily in most plant species. Species with excessively hairy or waxy leaves often require higher application rates to achieve control, most likely due to reduced penetration of the leaf surface.

Dust on the leaves will absorb glyphosate and prevent it from passing through the cuticle and epidermis.

Table 1: Environmental characteristics of Group M herbicides.

<table>
<thead>
<tr>
<th>Group M class</th>
<th>Active ingredient</th>
<th>Example trade name</th>
<th>Water solubility (mg/L)</th>
<th>Log Kow</th>
<th>Persistence in soil (half-life @ 20°C) (days)</th>
<th>Soil mobility (Koc/Kfoc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glycines</td>
<td>Glyphosate acid</td>
<td>Technical grade, not sold as a herbicide</td>
<td>15,700 at pH 7 11,600 at pH 2.5</td>
<td>0.0006–0.0017</td>
<td>24</td>
<td>20,870, non-mobile</td>
</tr>
<tr>
<td>Glyphosate isopropylamine</td>
<td>Roundup® CT</td>
<td>900,000 at pH 7 786,000 at pH 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glyphosate trimesium salt</td>
<td>Touchdown® Broadacre</td>
<td>4,300,000 at pH 7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Log Kow is the rate of herbicide that is soluble in octanol (organic solvent) v. water. It is a good indicator of the lipophilic or hydrophilic nature of a herbicide; larger the log Kow value the more lipophilic the herbicide; herbicides with values between –1 and 1 should move in the phloem following foliar application. Koc/Kfoc: >1000, binds strongly to soil; <500, moves in water. Solubility will vary with temperature and pH.
2M.2.1 Cellular absorption: passive diffusion and active absorption

The most common type of cellular absorption is passive, whereby the herbicide moves freely from an area of higher concentration in the symplast to an area of lower concentration in the cell, requiring no input of energy. (Refer to text box in Herbicide GrowNote: Group A for explanation of symplastic movement.)

Glyphosate can also be absorbed into plant cells via active absorption, which moves the herbicide molecule across the cell membrane against the concentration gradient. This increases the concentration of herbicide within the cell and it is facilitated by a protein carrier located in the cell membrane.

For a detailed explanation of this process, go to University of Nebraska Plant & Soil Science e-Library: Cellular absorption of herbicides—active absorption, general concepts.

2M.3 Translocation within the plant

Glyphosate is a relatively small molecule and is a weak acid herbicide so is readily translocated from the leaves to the growing tips (meristematic regions) of the shoots and roots. Up to 70% of absorbed glyphosate translocates away from the leaves but this occurs for only the first 48–72 hours after application. ³

Glyphosate primarily translocates basipetally in the plant (i.e. from the leaves to the roots) in association with sugars moving in the phloem. Glyphosate affects the carbon flow in the chloroplasts, ultimately reducing sugar production and movement of glyphosate in the phloem. (For more information on chloroplasts, see: How herbicides work. Biology to application, p. 53.) ⁴

Glyphosate is poor at killing small grasses. Very small (one-leaf) grasses are still growing on seed reserves and have not commenced sugar production via photosynthesis. This means little downward flow of sugars and glyphosate, ultimately leading to less reliable control. Glyphosate accumulates in the leaf tip and not the meristem in these small grasses. ⁵

2M.4 Timing of the double-knock

A double-knock is the sequential application of two weed control tactics applied in such a way that the second tactic controls any survivors of the first tactic. A common combination is glyphosate followed by paraquat or paraquat/diquat. The technique is primarily a herbicide-resistance management tool to minimise the chance of survival from the first control treatment (knock).

When glyphosate is the first knock, three to seven days should be allowed before the second knock is conducted. This allows sufficient time for glyphosate to translocate to the meristems in the shoots and roots. On-label rates should be used for both herbicides.

To allow translocation of glyphosate to the root systems of large plants and perennial species, the second knock should be delayed at least seven days.

For more information, see GRDC IWM manual for Australian Cropping systems. Section 4. Tactics for managing weed populations (pp. 128–132). ⁶

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2M.5 Symptoms

The first symptom of glyphosate application is wilting of the target plant. This is transient and is followed by chlorosis (pale yellow-green coloration) of the growing points and the new, expanding leaves. Chlorosis spreads throughout the plant, followed by necrosis (cell death) and the final death of the plant. Chlorosis and necrosis in some species are associated with an increase in tissue anthocyanins, which gives the plant a red coloration.

Sublethal glyphosate rates slow vegetative growth. New growth may appear bleached (white longitudinal striping in grasses) and is often deformed (downward bending ‘epinastic’ growth). Often there are multiple new deformed shoots and roots produced, and this can be mistaken for phenoxy herbicide damage. In large or perennial weeds, regrowth can occur after an initial brownout, often at the epicormic buds on the stems and trunks.

Photo 1: Dead wheat plants on the right versus a severely affected, multi-tillered plant on the left from glyphosate.

Photo: Tim McNee, NSW DPI

Photo 2: Bleached new growth from a sub-lethal rate of glyphosate on soybeans.

Photo: DPI&F
2M.5.1 Timeframe for symptoms and plant death

Rapidity of symptoms is determined by herbicide rate, plant susceptibility and size, and environmental conditions. Wilting occurs in first 24 hours, from which plants then recover. This is often missed by observers.

Under ideal conditions of warm temperatures, good soil moisture, small plants and high humidity, the first signs of leaf chlorosis on sensitive weed species may be evident within four–five days after application. In many instances, symptoms take 10–21 days to appear.

Where weeds are larger and/or more tolerant or where plant metabolism is slowed by cold temperatures, waterlogging or moisture stress, symptoms will appear much later. Older or larger plants have more stored reserves, which need to be run down before chlorosis will be evident. Woody perennials may take weeks or even months to begin to express chlorosis and subsequent leaf loss.

2M.6 Plant selectivity

Glyphosate is classified as a non-selective herbicide. This broad spectrum of weed control occurs because most plants have a common shikimate pathway and EPSP synthase binding site, coupled with no ability to metabolise glyphosate rapidly.

Glyphosate resistance has been introduced into crop species by inserting genes from bacteria that enable metabolism of glyphosate by the plant.

2M.7 Soil activity

Glyphosate has a typical field-soil half-life of 24 days (Table 1). This indicates moderate persistence in the soil, with soil breakdown occurring slowly via microbial degradation. However, glyphosate binds quickly and very tightly to the lattice structure of clay particles. This strong binding prevents uptake of glyphosate by germinating or emerging seedlings, or by roots of existing plants.

Strong binding to soil also usually prevents leaching and/or runoff.

Instances of plant damage caused by glyphosate residues have been recorded in soils with very low clay and organic matter content, but are uncommon.
2M.7.1 Breakdown pathways

Microbial degradation is the major pathway of glyphosate breakdown in the soil. The rate of degradation varies depending on the soil texture, temperature and moisture. Because there is negligible degradation of glyphosate within the plant, late-season applications for weed control or crop desiccation close to harvest can give detectable residues on straw and possibly in grain. When glyphosate is used close to harvest, it is therefore critical that label recommendations are followed, to ensure that maximum residue limits (MRLs) are not exceeded.

2M.8 Effect of environmental conditions on activity

Any environmental variable that affects plant growth will affect the translocation and efficacy of glyphosate. For example, drought stress was shown to reduce the efficacy of glyphosate by two to eight times on velvetleaf (Abutilon theophrasti). 7 The efficacy of low or marginal rates of herbicide can be greatly influenced by environmental conditions. Use of robust rates is the best way to reduce the influence of environmental variability on weed control.

2M.8.1 Light

Light drives photosynthesis and therefore has a major effect on plant growth and development. High intensity of light can also increase the amount and type of wax in the leaf cuticle.

High intensities of light (common in Australia) will increase the rate of uptake and translocation of glyphosate. However, the total amount of herbicide translocated is likely to be the same as for lower light intensity. High intensities of light also speed the rate of symptom development.

The time of day at which glyphosate is applied can have varying influences on glyphosate efficacy. Some research has shown that glyphosate interception and control in dicot species with diurnal leaf movement is reduced with night spraying as the weed leaves become more vertical. However, this change in leaf orientation at night only explained some of the difference in levels of control. 8 9

Some have postulated that night spraying reduces control because photosynthesis and the production of sugars cease, affecting translocation. 10

On the other hand, two separate research projects conducted in Western Australia investigating the control of the summer growing weed button grass (Dactyloctenium radulans) found little difference in level of control between night and day spraying. Increasing glyphosate rate and application volume made the greatest improvements in control. 11 12

2M.8.2 Temperature

The rate of absorption and translocation of glyphosate increases with temperature provided photosynthesis and transpiration are not limiting.

Species that can metabolise glyphosate, such as enhanced-metabolism resistant weed biotypes, will show higher levels of control at lower temperatures than at higher temperatures due to slower breakdown of the herbicide. However, research on glyphosate-resistant and -susceptible populations of awnless barnyard grass (Echinochloa colona) at the three–four-leaf stage found better control of both biotypes with the full label rate of glyphosate at day–night temperatures of 25°–20°C than 35°–30°C, at ~75% relative humidity for both treatments. This could be due to a range of factors including increased or different wax deposits on the leaves of plants grown at higher temperatures and possibly greater upward movement of glyphosate in the xylem with increased transpiration by the plant moving the herbicide away from the meristems.

2M.8.3 Humidity

Lower humidity increases the speed of droplet drying, meaning less time for glyphosate to be absorbed, because absorption ceases when the deposit dries (see Adjuvants below).

A full wetted cuticle will favour the penetration of water-soluble herbicides such as glyphosate. Low humidity is likely to increase plant transpiration, assuming soil moisture is adequate, increasing the upward movement of glyphosate in the xylem and reducing movement towards growing points in roots and rhizomes.

2M.8.4 Soil moisture stress

Low availability of soil moisture reduces the effectiveness of glyphosate through reduced translocation and photosynthesis. Moisture-stressed plants can also have smaller leaves, thicker cuticles and more wax deposits, reducing the effective target area and glyphosate absorption.

Research in northern New South Wales investigating the interaction in awnless barnyard grass between moisture stress and glyphosate efficacy showed that large plants needed higher rates of glyphosate. Control was improved when rain occurred prior to rather than after spraying.

2M.8.5 Rainfall

Rainfall prior to herbicide application affects available soil moisture as well as reducing the amount of crystalline wax on leaves. Rainfall prior to spraying will also wash off dust from the leaves. Dust on the leaves can absorb glyphosate and prevent it from passing through the cuticle and epidermis.

Rain shortly after glyphosate application will wash the herbicide off the leaves because it is hydrophilic. Rain-fast periods stated on labels vary between three and six hours, depending on the glyphosate formulation. The shorter rain-fast periods claimed on some labels are due to smaller glyphosate salt molecules and other premix adjuvants.

Research in northern New South Wales showed a strong link between glyphosate rate and rain-fast period. The higher the glyphosate rate the shorter the effective period for controlling seedling awnless barnyard grass, probably because of faster absorption of the higher concentrations of glyphosate.
2M.9 Spray application

Glyphosate has an optimum spray-application volume of 50–80 litres per hectare and it should be applied as a coarse, or very coarse, spray quality. (Note, however, that label recommendations vary.) Lower application volumes reduce the potential coverage whereas higher application volumes reduce the herbicide concentration in the solution, reducing the speed of absorption.

Because glyphosate is well translocated, the area of spray coverage can be as little as 6–8% as measured with water-sensitive paper.

2M.9.1 Water quality

pH

Glyphosate is a weak acid (pH 4.5–5). When added to the spray tank, glyphosate molecules break apart (disassociate) into negatively charged glyphosate ions, having given up hydrogen (H+) ions and lowering the pH of the spray solution.

NOTE: Test the pH of the water before considering lowering the pH of the spray solution; also test the pH of the spray following addition of the glyphosate. The optimum pH of the spray solution for glyphosate efficacy is 4.5–5.8.

However, reducing the pH of a spray solution is not recommended. Larger gains can be obtained by managing water hardness, increasing the glyphosate rate and ensuring a minimum coverage of 6%.

Water hardness

Hard water contains high levels of calcium, magnesium, bicarbonate, iron, zinc and aluminium cations. Hard water is most commonly defined as containing >150 mg/L (ppm) of calcium carbonate (CaCO₃). Using hard water reduces glyphosate efficacy because these cations bind to the negatively charged glyphosate ions. This in turn reduces the herbicide’s solubility, reducing leaf penetration. In extreme cases, it can cause the herbicide to precipitate and become sludge on the bottom of the spray tank. ¹⁷

Addition of ammonium sulfate to the spray solution prior to the addition of glyphosate will cause preferential binding between the cations in the water and the negatively charged sulfate ions in the ammonium sulfate, causing them to precipitate. This reduces subsequent binding with glyphosate.

Addition of ammonium sulfate also reduces (but does not eliminate) antagonism between glyphosate and some other herbicides such as triazines.

Suspended particles

Strong binding of glyphosate to clay particles leads to poor herbicide performance either through contamination of spray water or as dust on leaves. Dirty spray water containing suspended clay or organic material will bind and deactivate glyphosate.

As a rule-of-thumb, fill a 10-litre bucket with the water to be used, and place a coin on the bottom of the bucket. If the coin cannot be easily seen, the water is too dirty to use.

Spraying in dusty conditions can also deactivate glyphosate. This is a particular problem in lighter soil types prone to dust, and especially around the wheels tracks of sprayers (Photo 4).

Photo 4: Poor barnyard grass control in wheel tracks, most likely arising from dust at application, probably in association with early onset of moisture stress in compacted wheel tracks and poor coverage.

Photo: Mark Congreve

Water temperature

Low water temperatures can seriously affect tank mixes containing glyphosate, particularly if the pH of the mix is <5. Pesticides in the tank will come out of solution and form sludge in the sprayer.

There is also some evidence that cold water (~5°C) can reduce the efficacy of glyphosate.

2M.9.2 Adjuvants

The use of some adjuvants with glyphosate can increase the droplet spread and contact with the leaf surface. Other adjuvants can also reduce the speed of droplet evaporation on the leaf surface, thus allowing increased time for penetration.

Always read the product label.

The type, dose and combination of adjuvants used can have a significant impact on efficacy. Some ‘premium’ glyphosate formulations are loaded with a complete adjuvant ‘package’ and have no, or minimal, need for additional adjuvants. Other formulations, such as the popular ‘CT’ isopropylamine salt, are formulated with a minimal quantity of adjuvant and the label requires additional amounts of adjuvant depending on herbicide rate and carrier volume.

Oils are not generally recommended for use with glyphosate when controlling grasses because they can reduce the efficacy.

In summer, however, spray oils can reduce spray droplet evaporation and assist the efficacy of the partner herbicides in a tank mix. For example, potential tank-mix partners for glyphosate that benefit from the addition of spray oil include:

- triclopyr or 2,4-D for control of melons in fallow
- Group G herbicides such as Sharpen® (saflufenacil) in fallow and Valor® (flumioxazin) prior to sowing particular crops
- Group A grass-selective herbicides when used in glyphosate-tolerant canola or cotton.

Strategies to overcome potential antagonism between glyphosate and the spray oil when mixing with partner herbicide include:

- increasing the rate of glyphosate and ensuring optimum coverage
• applying the herbicides separately, the glyphosate first followed by the other herbicide four or five days later.

Typically, 2,4-D ester formulations are compatible with glyphosate. However, 2,4-D amine formulations require careful attention. Similar glyphosate and 2,4-D amine formulations will be compatible, e.g. glyphosate IPA and 2,4-D IPA formulations, but different amine formulations may not be compatible especially when using low spray volumes (higher concentrations of herbicides). This can reduce efficacy and may form precipitates that block nozzles. Combinations that often precipitate are potassium (K salt) and isopropylamine (CT) formulations of glyphosate with 2,4-D DMA formulations.

2M.10 Further reading

McWhorter CG, Jordan TN, Wills GD (1980) Translocation of 14C-glyphosate in soybeans (Glycine max) and johnson grass (Sorghum halepense). Weed Science 28,113–118.


Herbicide Group N modes of action

The Group N Mode of Action (MoA) contains one phosphinic acid herbicide, glufosinate, an inhibitor of glutamine synthase (Table 1).

Glufosinate is classified as Group H by the global Herbicide Resistance Action Committee (HRAC) and Group 10 by the Weed Science Society of America (WSSA) [http://hrac.tsstaging.com/tools/classification-look-up].

Glufosinate is a non-selective, contact-type herbicide that is active on both dicot and monocot weeds and grasses. It is, however, less effective on grasses and perennial species than on broadleaf annual weeds.

### Table 1: Herbicide included in Group N.

<table>
<thead>
<tr>
<th>Chemical class</th>
<th>Active ingredient</th>
<th>Product examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphinic acid</td>
<td>Glufosinate ammonium</td>
<td>Basta®, Liberty® 200</td>
</tr>
</tbody>
</table>


Glufosinate was first commercially released in 1995 and was first discovered in species of *Streptomyces* bacteria.

Glufosinate is used as a knockdown herbicide in orchards, plantations and crops as well as in non-agricultural areas.

Glufosinate-resistance genes originally extracted from two species of *Streptomyces* bacteria have been incorporated into maize, cotton, soybeans, sugar beet and canola. This Bayer-owned trait is called LibertyLink™ and the technology was developed by Bayer CropScience. Bayer estimates 24.3 million hectares of LibertyLink™ crops are being grown annually worldwide.

#### 2N.1 Mode of action and biochemical pathways

Glufosinate irreversibly binds to the enzyme glutamine synthase, which is responsible for combining ammonia (NH₃) and glutamate to form glutamine. Glutamine is used in the production of amino acids. Glutamine synthase also recycles ammonia produced by other biochemical pathways within the plant.

The binding to glutamine synthase is followed by a rapid accumulation of ammonia within the plant along with glyoxylate. Glyoxylate is an inhibitor of the RuBisCO enzyme, a key component in the non-light-mediated part of photosynthesis. This blocks photosynthesis and causes a build-up of toxic oxygen radicals.

This process occurs within the chloroplasts.

#### 2N.2 Absorption into the plant

Glufosinate is a highly water-soluble, weak acid herbicide. It is therefore absorbed through leaves and other green tissue via the aqueous pathway through the cuticle and epidermis.

A non-ionic surfactant is included in the formulation to ensure low surface tension of the solution and rapid movement through the aqueous pathway.

Most of the herbicide is absorbed within 72 hours. Temperature has no effect on the total amount of herbicide absorbed.
2N.3 Translocation within the plant

Glufosinate limits its own translocation due the rapid cessation in photosynthesis and cellular destruction following absorption. It is rapidly absorbed into the apoplast, including the xylem, and the symplast, including the phloem.

Translocation rate varies with weed species and growing conditions. Phloem mobility is reduced and xylem transport enhanced in cooler temperatures. This in turn reduces the amount of herbicide being translocated to the meristems, which can then allow regrowth. In addition, less ammonia is produced at lower temperatures.

2N.4 Symptoms and timeframe for symptoms and plant death

Symptoms vary with plant type, herbicide rate, temperature and humidity.

Usually, the first symptom is a faint green discoloration on the leaves at ~24–48 hours post-application, associated with a rapid rise in plant-tissue ammonia levels over this time.

In less susceptible species, or at lower effective herbicide rates and lower temperatures, symptoms of leaf-tip burning, tip curling and patchy yellowing will occur over 7–10 days.

Small susceptible weeds exposed to good spray coverage will develop even yellowing of the leaves within 3–7 days followed by complete desiccation in 10–15 days. Under cool conditions, desiccation may take up to 30 days.

Symptoms develop much faster with high light intensity, temperatures >20°C but <33°C, and relative humidity >50%.

If plant meristems remain green, the plant will re-grow.
Photo 2: Glufosinate chlorosis and necrosis on oat plants 5 days after treatment. Photo: Andrew Storrie, Agronomo

**2N.5 Plant selectivity**

Differences in tolerance between weed species have been found to be as high as 70-fold. This appears to be due to differences in:

- rate and extent of herbicide uptake
- translocation within the plant—differences in partitioning of the herbicide between the phloem and the xylem
- capacity to detoxify the herbicide.

All species are more susceptible at higher temperatures (i.e. 30°C > 20°C > 10°C), and when the relative humidity is >50%.

There are differences in susceptibility within grasses, non-grass monocots and broadleaf species.

Grasses tend to need higher rates than broadleaf weeds to achieve control.

Age of the plant will influence rates of herbicide absorption because of thickness and permeability of cuticles.

**2N.6 Soil activity**

Despite being highly water-soluble, little glufosinate is absorbed by roots, owing to rapid microbial degradation (Table 2).

Soil sterilisation will result in soil activity, with potential damage to the crop.

Glufosinate remains active on inert surfaces such as plastic mulch and it can be later washed off, causing damage to crops.
### Table 2: Environmental characteristics of the Group N herbicide, phosphinic acid.

<table>
<thead>
<tr>
<th>Active ingredient</th>
<th>Example trade name</th>
<th>Water solubility</th>
<th>Log Kow</th>
<th>Persistence in soil (half-life @ 20°C)</th>
<th>Soil mobility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glufosinate ammonium</td>
<td>Basta®</td>
<td>1,370,000 mg/L</td>
<td>–4.6</td>
<td>7 days</td>
<td>Slightly mobile</td>
</tr>
</tbody>
</table>

Log Kow, ratio of herbicide that is soluble in octanol (organic solvent) v. water; it is a good indicator of the lipophilic or hydrophilic nature of a herbicide; the larger the log Kow value the more lipophilic the herbicide; herbicides with values between –1 and 1 should move in the phloem following foliar application.

### 2N.7 Effect of environmental conditions on activity

#### 2N.7.1 Light

Efficacy of glufosinate increases with increasing light intensity, due to increased photosynthesis.

#### 2N.7.2 Temperature

As temperature increases, the rate of uptake of herbicide increases provided respiration and photosynthesis are not limited by the conditions. However, the total amount of herbicide absorbed does not change.

Higher temperatures increase the rate of photosynthesis; therefore, a greater amount of reactive oxides will be produced, shortening the time for symptoms to develop.

#### 2N.7.3 Humidity

Glufosinate has optimum efficacy when relative humidity is at least 50%. Humidity increases the lifespan of hydrated droplets of Group N herbicide on the leaf surface.

High humidity also makes the aqueous pathway through the cuticle more permeable to water-soluble herbicides.

In addition, plants growing under high humidity have thinner cuticles and are generally easier to control.

#### 2N.7.4 Soil moisture stress

Stressed plants have thicker cuticles, which will increase the length of the aqueous path accessed by Group N herbicide. The additional waxes or hairs can increase herbicide runoff and droplet bounce, reducing herbicide coverage.

Moisture stress means lower rates of photosynthesis; therefore, fewer free electrons will be available for oxygen radicals.

#### 2N.7.5 Rainfall

Glufosinate is rain-fast for six hours.

Because glufosinate is stable on surfaces such as plastic it can be washed off in rain and damage plants that it contacts.

#### 2N.8 Spray application

Glufosinate is poorly translocated within the plant owing to its rapid action, so spray coverage is critical. The spray target should be at least 15% coverage.

Label recommendations are 100 litres per hectare (L/ha) for fallow. A medium spray quality is recommended. For orchards, plantations, vineyards, sugarcane, other row crops, non-agricultural areas, etc., the Basta® label states 300–500 L/ha applied by boom, shielded/hooded or directed spray.
2N.8.1 Adjuvants

Glufosinate contains a pre-formulated wetter, and additional surfactant is required only when application volumes are >500 L/ha, or when pines (*Pinus* spp.) are the target species.

Read the label for recommended use of adjuvants.

2N.8.2 Water quality

The label recommends the use of clean water.

**pH**

Glufosinate is a weak acid herbicide, so will lower the pH of the spray solution when added to the tank. Avoid water with pH ≥8.

**Hardness**

Water with high levels of cations and bicarbonate should be avoided. Typically, water hardness above 250 to 350ppm (CaCO$_3$ equivalents) should be treated before using herbicides.

**Turbidity**

Low levels of turbidity will not interfere with the efficacy of glufosinate.

2N.9 Further reading


Herbicide Group Q modes of action

The Group Q Mode of Action (MoA) herbicides inhibit cyclisation of carotenoids, blocking the formation of xanthophylls. Xanthophyll carotenoids are important in buffering the energy from light reactions in photosynthesis. Symptoms include the bleaching of new growth.

Group Q herbicides are classified as Group 11 by the global Herbicide Resistance Action Committee (HRAC) and Group F3 by the Weed Science Society of America (WSSA) (http://hrac.tsstaging.com/tools/classification-lookup).

There are two chemical classes within the Group Q MoA as shown in Table 1. These classes are different types of chemicals; however, they affect the same biochemical pathways in the plant.

Table 1: Herbicides included in Group Q.

<table>
<thead>
<tr>
<th>Chemical class</th>
<th>Active ingredient</th>
<th>Product examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isoxazolidinones</td>
<td>Clomazone</td>
<td>Magister®, Director® 480</td>
</tr>
<tr>
<td>Triazoles</td>
<td>Amitrole</td>
<td>Amitrole T, Amitrole 250, Alliance®, Para-Trooper (PM)</td>
</tr>
</tbody>
</table>

Alliance® and Para-Trooper contain more than one active constituent.

Amitrole was the first synthetic, non-selective herbicide produced, being commercialised in 1959. Clomazone was commercialised around 1985.

Amitrole is often formulated with ammonium thiocyanate, which reduces its degradation within the plant. Use of amitrole declined with the introduction of glyphosate; however, it has come back into favour because of the increasing number of glyphosate-resistant weed populations. It is now used in combinations with paraquat and other herbicides to control weeds in fallows, on roadsides, and in other non-crop areas.

In Australia, clomazone is used to control annual grasses in rice crops. It is also registered for use in cucurbits, beans, poppies, potatoes and tobacco. In North America and Europe, clomazone is used in crops of soybeans, cotton, vegetables and sugarcane.

2Q.1 Mode of action and biochemical pathways

Clomazone is metabolised to the active 5-keto form in the plant. This form then blocks deoxxyxylulose 5-phosphate synthase, a key enzyme of plastid isoprenoid synthesis, at the start of the pathway for carotenoid biosynthesis.

Amitrole acts at the third site for herbicides that inhibit carotenoid biosynthesis—cyclisation. Lycopene, a linear intermediate, is cyclised (6-atom rings) at both ends to form the carotenones, which can in turn be hydroxylated to form the xanthophyll carotenoids. Amitrole inhibits cyclisation of lycopene.

Amitrole may also affect cell division and elongation.

For more information, see Plant & Soil Sciences eLibrary: Herbicides that act through photosynthesis. Inhibitors of carotenoid biosynthesis.
**2Q.2 Absorption into the plant**

Amitrole is highly water-soluble and is absorbed by the roots (Table 2). It also rapidly penetrates the leaf cuticle. Root uptake tends to be minor because amitrole is quickly decomposed in the soil. Amitrole may be partially bound to cuticular waxes depending on the species. Diffusion across the plasma membrane is likely to be a passive process.

Clomazone is poorly absorbed through the cuticle and epidermis and poorly translocated in the phloem. However, it is readily absorbed by roots and emerging shoots (i.e. the coleoptile of grasses and the broadleaf hypocotyl).

**Table 2: Environmental characteristics of Group Q herbicides.**

<table>
<thead>
<tr>
<th>Group Q class</th>
<th>Active ingredient</th>
<th>Example trade name</th>
<th>Water solubility (mg/L)</th>
<th>Log Kow</th>
<th>Soil persistence (half-life @ 20°C) (field)</th>
<th>Soil mobility (Koc/Kfoc)</th>
<th>Volatility (Henry’s Law constant, 25°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isoxazolidinones</td>
<td>Clomazone</td>
<td>Magister®</td>
<td>1102</td>
<td>2.54</td>
<td>43</td>
<td></td>
<td>300, moderate</td>
</tr>
<tr>
<td>Triazoles</td>
<td>Amitrole</td>
<td>Alliance®</td>
<td>264,000</td>
<td>-0.97</td>
<td>16</td>
<td></td>
<td>87, moderate</td>
</tr>
</tbody>
</table>

Log Kow, ratio of herbicide that is soluble in octanol (organic solvent) v. water; it is a good indicator of the lipophilic or hydrophilic nature of a herbicide; the larger the log Kow value the more lipophilic the herbicide; herbicides with values between −1 and 1 should move in the phloem following foliar application. Koc/Kfoc: >1000, binds strongly to soil, <500, moves in water.


**2Q.3 Translocation within the plant**

Amitrole is polar and non-ionised and is strongly mobile in both the phloem and xylem. It is largely retained in the phloem once it has crossed the plasma membrane. The herbicide accumulates at the growing points.

Clomazone is translocated in the xylem to the growing points.

**2Q.4 Symptoms**

Symptoms on larger plants begin with bleaching of the new growth. This bleaching and yellowing spreads through the plant and leads to wilting and necrosis or browning.

Seedlings will emerge from clomazone-treated soil, but are bleached and become necrotic after several days.

Larger plants treated post-emergent with clomazone show bleaching of the leaves. Similar symptoms occur in adjacent plants with vapour drift from post-emergent applications.

**2Q.4.1 Timeframe for symptoms and plant death**

Rate of development of symptoms and subsequent damage and death depend on the plant species, herbicide dose, age and size of plant, and rate of plant growth. After application, death occurs from as early as several days for emerging seedlings to four to eight weeks for larger plants.

Compared with glyphosate, the development of symptoms and the death of weeds treated with amitrole are very slow.
Photo 1: Amitrole causing bleaching on new growth in barley.
Photo: Andrew Storrie, Agronomo

Photo 2: Amitrole causing bleaching in canola.
Photo: Andrew Storrie, Agronomo
2Q.5 Crop selectivity

Amitrole is non-selective (Table 3). It does exhibit some synergism when mixed with paraquat (Group L). Amitrole decomposes quickly in the soil, so it is unlikely that there will be root uptake.

When using clomazone, the main tactic for crop selectivity is separation from the band of chemical. This is similar to the requirement with Group D herbicides. Clomazone should not be applied to soil intended for seedling transplants (except for tobacco).

Rice can detoxify clomazone quickly, unless it receives direct herbicide contact or it is stressed from cold, deep water or salinity.

Table 3: Differences in efficacy between Group Q chemical classes.

<table>
<thead>
<tr>
<th>Group Q class</th>
<th>Herbicide example</th>
<th>Crops</th>
<th>Weeds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isoxazolidinones</td>
<td>Clomazone</td>
<td>Rice</td>
<td>Echinochloa spp., suppresses silvertop grass</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Leptochloa fusca)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cucurbits, green beans, navy beans,</td>
<td>Post-plant pre-emergent and post-emergent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>poppies, potatoes, tobacco</td>
<td>control of a range of broadleaf weeds</td>
</tr>
<tr>
<td>Triazoles</td>
<td>Amitrole</td>
<td>Orchards, vineyards, eucalyptus and pine</td>
<td>Wide range of grasses, non-grass monocots</td>
</tr>
<tr>
<td></td>
<td></td>
<td>plantations, canola, wheat, barley, oats,</td>
<td>and broadleaf species</td>
</tr>
<tr>
<td></td>
<td></td>
<td>rye, triticale, faba beans, field peas,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>lupins, cotton, mung beans, sorghum,</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>potatoes, a range of pastures</td>
<td></td>
</tr>
</tbody>
</table>

2Q.6 Effect of environmental conditions on activity

Clomazone is poorly translocated from a foliar application. Absorption via the roots is important for effective control; therefore, available soil moisture is one of the critical factors in determining the efficacy of this herbicide.

Clomazone should not be used on soils that contain <15% clay and 2% organic matter. (This does not apply to tobacco or poppy crops, which have a higher tolerance to clomazone at label rates.)

2Q.6.1 Light

Group Q herbicides need light to produce damaging radicals within the photosynthetic system. Bright sunlight will speed development of symptoms and ultimately will speed control.

2Q.6.2 Temperature

As temperature increases, the rate of photosynthesis increases, speeding the production of radicals within the photosynthetic system. Frosts and cold stress will reduce the effectiveness of these herbicides.
2Q.6.3 Humidity

Plants growing in higher humidity have less epidermal wax on the leaf surface than plants growing in low humidity. High humidity (>50%) will increase the amount of amitrole entering the plant, owing to a hydrated cuticle and the likelihood of thinner cuticular waxes. High humidity will increase the life of herbicide droplets on the leaf, increasing the time for diffusion to occur.

2Q.6.4 Soil moisture stress

Moisture-stressed plants have thicker cuticles, and these will slow the absorption of foliar-applied amitrole. Addition of certain adjuvants can assist herbicide absorption into the plant.

Adequate moisture is required at the soil surface to enable root absorption of clomazone. Drying of the surface soil will reduce the level of weed control when using this herbicide.

Clomazone use in rice is not affected by moisture stress because it is applied at permanent flood.

2Q.6.5 Rainfall

The rain-fast period for foliar application of amitrole is six hours.

Light rain will improve plant uptake of clomazone from the soil.

2Q.7 Spray application

Amitrole is well translocated within the plant; however, it is not as active a herbicide as glyphosate, so it requires good coverage to maximise the amount of herbicide entering the plant.

Product labels (e.g. Amitrole T) recommend applying 100–500 litres (L) per hectare for optimum coverage, but they do not mention spray quality. Medium to coarse spray quality should be used, depending on the situation.

If amitrole is in a tank mix with paraquat, application must be as a medium to coarse (Alliance®) or medium (Para-Trooper) spray quality. Target coverage should be 10–15% as measured with water-sensitive paper.

Soil-applied herbicides need even coverage; however, they can be applied in a coarse to extremely coarse spray quality. The clomazone label recommends at least a medium spray quality, although this is more aimed at drift reduction. If tank-mixed with a knockdown herbicide, application should be in the relevant spray quality for that knockdown herbicide.

2Q.7.1 Adjuvants

Amitrole and amitrole + paraquat mix may need addition of a non-ionic surfactant if application volumes are below 400 mL per 100 L solution.

If clomazone is applied by air, it must have a drift retardant added.

2Q.7.2 Water quality

Amitrole is not affected by a wide range of water qualities. However, when tank-mixed with paraquat the water requirements for paraquat must be adhered to, i.e. water should be clean and free from clay, silt and algae.

Hard water should be avoided when using clomazone.
2Q.8 Further reading


Herbicide Group Z modes of action

The Group Z Mode of Action (MoA) herbicides have unknown and diverse sites of action. This makes Group Z the receptacle for herbicides that do not fit into other groups. This is partly because we are still unclear about how these herbicides work despite their use for decades.

Group Z are also classified as Group Z by the global Herbicide Resistance Action Committee (HRAC). Because each class of chemical acts on different pathways, the Weed Science Society of America (WSSA) classifies flamprop-m-methyl as Group 25 and organoarsenicals as Group 17, whereas endothal is not classified (NC) (http://hrac.tsstaging.com/tools/classification-lookup).

Flamprop-m-methyl is used for the post-emergent control of wild oats in bread wheat and triticale.

In Australia, endothal is registered for the control of winter grass in turf. In the northern hemisphere, it has been used as a post-plant incorporated herbicide in sugar beets to control annual broadleaf and grass weeds, and as a pre-harvest desiccant in potatoes and alfalfa (lucerne) and clover seed crops. It has also been used as an aquatic herbicide to control algae and a number of submerged aquatic weeds.

Different forms of arsenic have been used as herbicides since the early 1900s. The organoarsenical herbicide MSMA (monosodium methyl arsenate) is used for post-emergent control of annual and perennial grasses and broadleaf weeds in cotton, sugarcane and non-crop areas, control of Opuntia spp., control of annual grasses in turf, and control of burrs in cotton and non-crop areas. The organoarsenical herbicide DSMA (disodium methyl arsenate) is used for post-emergent control of annual grasses in turf. Use of organoarsenical herbicides has declined markedly during the past 15 years.

There are three chemical classes within the Group Z MoA as shown in Table 1.

Table 1: Herbicides included in Group Z.

<table>
<thead>
<tr>
<th>Chemical class</th>
<th>Active ingredient</th>
<th>Product examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arylaminopropionic acids</td>
<td>Flamprop-m-methyl</td>
<td>Judgement®</td>
</tr>
<tr>
<td>Dicarboxylic acids</td>
<td>Endothal</td>
<td>Poachek®</td>
</tr>
<tr>
<td>Organoarsenicals</td>
<td>DSMA, MSMA</td>
<td>Trinoc, Daconate®</td>
</tr>
</tbody>
</table>

Trinoc contains more than one active constituent.


2Z.1 Mode of action and biochemical pathways

Flamprop-m-methyl is a mitotic disrupter with an anti-microtubule mechanism of action that affects orientation of spindle and phragmoplast microtubules, possibly by minus-end microtubule disassembly.

Endothal inhibits lipid and protein synthesis in some species while causing increased electrolyte leakage and increased levels of polyphenols, followed by necrosis.

MSMA and DSMA are thought to affect cell membrane integrity.
## 2Z.2 Absorption into the plant

Flamprop-m-methyl is a pre-herbicide and is converted to the active form inside the plant. It is readily absorbed through the cuticle and epidermis of the plant.

Endothal is rapidly absorbed by roots and can rapidly penetrate the leaf cuticle as the undissociated parent acid.

Organoarsenicals are readily absorbed by foliage.

## 2Z.3 Translocation within the plant

Flamprop-m-methyl appears to be well translocated within the phloem.

Endothal is translocated from the roots to foliar parts of the plant by the xylem; it is not phloem-mobile. Endothal can cause callus formation in the phloem sieve tubes, which helps to limit phloem mobility.

Organoarsenicals are translocated in both the phloem and xylem because they are weak acid herbicides with high levels of water solubility (Table 2).

### Table 2: Environmental characteristics of Group Z herbicides.

<table>
<thead>
<tr>
<th>Group Z class</th>
<th>Active ingredient</th>
<th>Example trade name</th>
<th>Water solubility (mg/L)</th>
<th>Log Kow</th>
<th>Soil persistence (half-life @ 20°C) (days)</th>
<th>Soil mobility (Koc/Kfoc)</th>
<th>Drift potential (Henry’s Law constant, 25°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arylaminopropionic acids</td>
<td>Flamprop-m-methyl</td>
<td>Judgement®</td>
<td>35</td>
<td>3.33</td>
<td>10</td>
<td>n.a.</td>
<td>Non-volatile</td>
</tr>
<tr>
<td>Dicarboxylic acids</td>
<td>Endothal</td>
<td>Poachek®</td>
<td>100,000</td>
<td>1.91</td>
<td>7</td>
<td>85, moderate</td>
<td>Non-volatile</td>
</tr>
<tr>
<td>Organoarsenicals</td>
<td>DSMA</td>
<td>Trinoc</td>
<td>43,200</td>
<td>–5.3</td>
<td>269</td>
<td>1680, slight</td>
<td>Non-volatile</td>
</tr>
<tr>
<td></td>
<td>MSMA</td>
<td>Daconate®</td>
<td>580,000</td>
<td>–3.1</td>
<td>200</td>
<td>n.a.</td>
<td>Non-volatile</td>
</tr>
</tbody>
</table>

Log Kow, ratio of herbicide that is soluble in octanol (organic solvent) v. water; it is a good indicator of the lipophilic or hydrophilic nature of a herbicide; the larger the log Kow value the more lipophilic the herbicide; herbicides with values between –1 and 1 should move in the phloem following foliar application. Koc/Kfoc >1000, binds strongly to soil; <500, moves in water; n.a., Not available.


## 2Z.4 Symptoms

Application of flamprop-m-methyl leads to rapid cessation of growth and a change in the plant colour to a blue-green. The youngest leaf unrolls and tiller sheaths begin to open and detach from the shoot. High rates of herbicide lead to plant death, whereas spray-topping rates and timing lead to the inflorescence not fully emerging from the boot. The inflorescence appears as though it has been stem-frosted.

Endothal causes rapid desiccation and browning of foliage. Endothal present in the soil and absorbed by the roots causes shortening of roots.

Organoarsenicals causes chlorosis with little or no wilting, leading to desiccation. Cotton seedlings can exhibit reddening.
2Z.4.1 Timeframe for symptoms and plant death

Rate of development of symptoms and subsequent damage and death depend on the plant species, herbicide dose, age and size of plant, and rate of plant growth.

Flamprop-m-methyl will cause subtle changes within two to three days after application. Plant growth ceases within hours. Plant discoloration and death can take one to five weeks.

Organoarsenicals will cause severe chlorosis and desiccation in less than one day with high temperatures and light. Symptoms may take five to 10 days to appear at temperatures <25°C.

2Z.5 Crop selectivity

Selectivity of flamprop-m-methyl depends on the methyl ester undergoing hydrolysis to form the biologically active acid, which is usually detoxified quickly in wheat and triticale by conjugation (Table 3). Cultivars containing the SR26 stem rust gene are known to be more susceptible to this herbicide than other cultivars.
Selectivity with endothal appears to be rapid metabolism within the plant. The organoarsenicals herbicides are conjugated with sugars, amino acids, other organic acids and other molecules to make them nontoxic.

Table 3: Differences in efficacy between Group Z chemical classes.

<table>
<thead>
<tr>
<th>Herbicide</th>
<th>Crops</th>
<th>Weeds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arylaminopropionic acids</td>
<td>Flamprop-methyl</td>
<td>Bread wheat and triticale</td>
</tr>
<tr>
<td>Dicarboxylic acids</td>
<td>Endothal</td>
<td>Post-emergent control of wild oats (Avena spp.)</td>
</tr>
<tr>
<td>Organoarsenicals</td>
<td>DSMA</td>
<td>Post-emergent control of annual grasses</td>
</tr>
<tr>
<td></td>
<td>MSMA</td>
<td>Cotton, sugarcane, non-crop areas, couch turf</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post-emergent control of a range of grass and broadleaf species, Opuntia spp.</td>
</tr>
</tbody>
</table>

2Z.6 Effect of environmental conditions on activity

2Z.6.1 Light

Photodegradation is not a major path of breakdown. High levels of light increase the speed of action of organoarsenical herbicides.
2Z.6.2 Temperature

Warmer temperatures speed the action of flamprop-m-methyl and organoarsenicals, with temperatures >20°C recommended for application. Increased plant growth rates increase the translocation of these herbicides, speeding the effect in susceptible species and increasing the rate of herbicide metabolism in tolerant species.

Endothal should not be used when temperatures exceed 25°C because it will scorch the turf.

2Z.6.3 Humidity

Low relative humidity increases the speed of development of symptoms with organoarsenicals.

2Z.6.4 Soil moisture

Adequate soil moisture is required to maintain active plant growth to assist with translocation of the herbicides and blocking of the targeted chemical pathway.

Flamprop-m-methyl is particularly sensitive to moisture stress because it is mainly translocated in the phloem.

2Z.6.5 Rainfall

MSMA has a six-hour rain-fast period, and the label for Trinoc (DSMA + MCPA) states four hours. Flamprop-m-methyl is rain-fast after four hours. Differences are due to differential rates of absorption into the leaf.

2Z.7 Spray application

Flamprop-m-methyl should be applied as a medium spray-quality droplet in up to 100 litres spray volume.

The label for Poachek® (endothal) suggests that it should be applied with a fine spray. This is contrary to good practice, and endothal should be applied as a medium spray quality with an application volume to give high levels of coverage, such as 100–200 litres per hectare.

Labels for MSMA and DSMA do not recommend a spray quality, but they should be applied as a coarse spray quality with a sufficiently high application volume to give at least 15% coverage. Off-target movement of organoarsenicals herbicides should be avoided.

2Z.7.1 Adjuvants

A crop oil should be added to flamprop-m-methyl only for spray-topping.

Endothal does not require an adjuvant.

Organoarsenicals do not need adjuvants; they are weak acids and highly water-soluble.

2Z.7.2 Water quality

Organoarsenicals are sensitive to hard water because they are weak acids. High levels of cations, including iron, lead to the formation of insoluble forms, which precipitate in the tank.

Flamprop-m-methyl and endothal are not sensitive to water quality.
2Z.8  Further reading


Herbicide resistance

Herbicide resistance is prevalent in Australian agriculture, costing the industry nearly $200 million every year. It has spread and diversified to become a key constraint to crop production in all states. ¹

The move to more continuous cropping, the reduction in tillage and the increase in farm size have contributed to the rise in resistance. All of these, particularly the adoption of no-till, have contributed to increased reliance on herbicides for weed control. ²

Herbicide resistance evolves following the intensive use of herbicides for weed control. In any weed population, owing to genetic diversity, there are likely to be a small number of individuals naturally resistant to herbicides, even before the herbicides are used. When a herbicide is used, these individuals survive and set seed, whereas the majority of susceptible plants are killed. Continued use of the same herbicide or herbicide group will eventually result in a significant portion of the weed population with resistance. ³

Herbicide resistance fact box

source: GRDC IWM for Australian Cropping Systems, Chapter 2: Herbicide resistance

- Resistance is the inherited ability of an individual plant to survive and reproduce following a herbicide application that would kill a wild-type individual of the same species.
- Forty-six weed species in Australia currently have populations that are resistant to at least one herbicide Mode of Action (MoA).
- Australian weed populations have developed resistance to 13 different MoAs.
- Herbicide-resistant individuals may be present at very low frequencies in weed populations before any herbicide is first applied.
- The frequency of naturally resistant individuals in a population will vary greatly within and between weed species.
- A weed population is defined as resistant when a herbicide at a label rate that once controlled the population is no longer effective. (Some testing services use an arbitrary figure of 20% survival of the test population for defining resistance; others rank any plants that survive treatment—S, R, RR, RRR).
- The proportion of herbicide-resistant individuals will increase (through selection pressure) in situations where the same herbicide MoA is applied repeatedly and the survivors are not subsequently controlled.
- Herbicide resistance in weed populations is permanent as long as seed remains viable in the soil. Only weed density can be reduced, not the ratio of resistant to susceptible.

Four main factors influence the evolution of resistance:

- **The intensity of selection pressure.** This refers to how many weeds are killed by the herbicide. It is good practice to use robust labelled rates of herbicides to control weeds, as this will lead to the highest and most consistent levels of weed control. Failure to control weeds adequately will lead to increases in weed populations and put pressure on all herbicides used.

- **The frequency of use of a herbicide or MoA group.** For most weeds and herbicides, the number of years of herbicide use is a good measure of selection intensity. The more often a particular herbicide is used, the higher the selection pressure and the greater the risk of developing herbicide resistance.

- **The frequency of resistance present in untreated populations.** If the frequency of resistant genes in a population is relatively high, such as with Group B herbicides, resistance will occur quickly. If the frequency is low, such as with Group M herbicides, resistance will occur more slowly.

- **The biology and density of the weed.** Weed species that produce large numbers of seed and have a short-lived seedbank in the soil will evolve resistance faster than weed species with a long-lived seedbank. This is because a greater proportion of the population of a species with a short-lived seedbank will be exposed to the herbicide over a shorter period than would occur with a species with a long-lived seedbank. Weed species with greater genetic diversity are also more likely to evolve resistance. For example, annual ryegrass (*Lolium rigidum*) and wild radish (*Raphanus raphanistrum*) have considerable genetic variation and must cross-pollinate between different plants to produce fertile seed meaning they share genes between plants. Resistance is more likely to be detected in larger weed populations.  

### 3.1 State of play

Herbicide-resistant weed populations are now found throughout all cropping areas of Australia and their incidence continues to increase. There is also an increase in the occurrence of weed species on the same farm with resistance to different herbicide MoAs, as well as an increase in the number of weed populations with resistance to more than one MoA. This makes management of resistant weeds increasingly difficult, complex and expensive.

There are 47 weed species in Australia with resistance to one or more of 13 herbicide MoA groups. (See the full list of Australian herbicide MoA groups at: [http://www.croplife.org.au/resistance-strategy/2016-herbicide-moa-table/](http://www.croplife.org.au/resistance-strategy/2016-herbicide-moa-table/).)

Table 1 has been drawn from the International Survey of Herbicide Resistant Weeds conducted by weed scientists in over 80 countries and funded by the Global Herbicide Resistance Action Committee and CropLife International.  

---


<table>
<thead>
<tr>
<th>#</th>
<th>Species</th>
<th>Common name</th>
<th>State</th>
<th>First year</th>
<th>Resistance according to SoA (MoA Group in parentheses)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><em>Lolium rigidum</em></td>
<td>Annual ryegrass/Wimmera grass</td>
<td>NSW</td>
<td>1985</td>
<td><strong>Multiple resistance: three SoA:</strong> ACCase inhibitors (A)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ALS inhibitors (B)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Microtubule inhibitors (D)</td>
</tr>
<tr>
<td>2</td>
<td><em>Avena ludoviciana</em></td>
<td>Ludo wild oats</td>
<td>NSW</td>
<td>1989</td>
<td>ACCase inhibitors (A)</td>
</tr>
<tr>
<td>3</td>
<td><em>Avena fatua</em></td>
<td>Wild oats</td>
<td>NSW</td>
<td>1991</td>
<td>ACCase inhibitors (A)</td>
</tr>
<tr>
<td>4</td>
<td><em>Cyperus difformis</em></td>
<td>Dirty Dora</td>
<td>NSW</td>
<td>1994</td>
<td>ALS inhibitors (B)</td>
</tr>
<tr>
<td>5</td>
<td><em>Sagittaria montevidensis</em></td>
<td>Arrowhead</td>
<td>NSW</td>
<td>1994</td>
<td>ALS inhibitors (B)</td>
</tr>
<tr>
<td>6</td>
<td><em>Damasonium minus</em></td>
<td>Starfruit</td>
<td>NSW</td>
<td>1994</td>
<td>ALS inhibitors (B)</td>
</tr>
<tr>
<td>7</td>
<td><em>Sisymbrium orientale</em></td>
<td>Indian hedge mustard</td>
<td>NSW</td>
<td>1994</td>
<td>ALS inhibitors (B)</td>
</tr>
<tr>
<td>8</td>
<td><em>Sinapis arvensis</em></td>
<td>Charlock</td>
<td>NSW</td>
<td>1994</td>
<td>ALS inhibitors (B)</td>
</tr>
<tr>
<td>9</td>
<td><em>Phalaris paradoxa</em></td>
<td>Paradoxa grass</td>
<td>NSW</td>
<td>1997</td>
<td>ACCase inhibitors (A)</td>
</tr>
<tr>
<td>10</td>
<td><em>Lolium rigidum</em></td>
<td>Wimmera ryegrass</td>
<td>NSW</td>
<td>1997</td>
<td>EPSP synthase inhibitors (M)</td>
</tr>
<tr>
<td>11</td>
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**Table 1:** Herbicide-resistant weeds in Australia as at January 2017, including type of resistance (site of action, SoA) and the first year that resistance (single or multiple) was detected within each state.
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<th>#</th>
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<th>Common name</th>
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<th>First year</th>
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## Section 3 Herbicide Use

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<tr>
<td>99</td>
<td><em>Chloris truncata</em></td>
<td>Windmill grass</td>
<td>Vic.</td>
<td>2015</td>
<td>EPSP synthase inhibitors (M)</td>
</tr>
<tr>
<td>100</td>
<td><em>Lactuca semiola</em></td>
<td>Prickly lettuce</td>
<td>Vic.</td>
<td>2015</td>
<td>EPSP synthase inhibitors (M)</td>
</tr>
<tr>
<td>101</td>
<td><em>Lolium rigidum</em></td>
<td>Wimmera ryegrass</td>
<td>Vic.</td>
<td>2015</td>
<td>Lipid inhibitors (J)</td>
</tr>
<tr>
<td>102</td>
<td><em>Sonchus oleraceus</em></td>
<td>Annual sowthistle</td>
<td>Vic.</td>
<td>2015</td>
<td>Synthetic auxins (I)</td>
</tr>
<tr>
<td>103</td>
<td><em>Lolium rigidum</em></td>
<td>Wimmera ryegrass</td>
<td>WA</td>
<td>1982</td>
<td><strong>Multiple resistance: three SoA:</strong> ACCCase inhibitors (A) ALS inhibitors (B) Microtubule inhibitors (D)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>104</td>
<td><em>Lolium rigidum</em></td>
<td>Wimmera ryegrass</td>
<td>WA</td>
<td>1984</td>
<td>ALS inhibitors (B)</td>
</tr>
<tr>
<td>105</td>
<td><em>Lolium rigidum</em></td>
<td>Wimmera ryegrass</td>
<td>WA</td>
<td>1984</td>
<td>Microtubule inhibitors (D)</td>
</tr>
<tr>
<td>106</td>
<td><em>Avena fatua</em></td>
<td>Wild oats</td>
<td>WA</td>
<td>1985</td>
<td>ACCase inhibitors (A)</td>
</tr>
<tr>
<td>107</td>
<td><em>Lolium rigidum</em></td>
<td>Wimmera ryegrass</td>
<td>WA</td>
<td>1988</td>
<td>Carotenoid biosynthesis inhibitors (F)</td>
</tr>
<tr>
<td>108</td>
<td><em>Lolium rigidum</em></td>
<td>Wimmera ryegrass</td>
<td>WA</td>
<td>1988</td>
<td>Photosystem II inhibitors (C)</td>
</tr>
<tr>
<td>109</td>
<td><em>Brassica tournefortii</em></td>
<td>Wild turnip</td>
<td>WA</td>
<td>1992</td>
<td>ALS inhibitors (B)</td>
</tr>
<tr>
<td>110</td>
<td><em>Sisymbrium orientale</em></td>
<td>Indian hedge mustard</td>
<td>WA</td>
<td>1994</td>
<td>ALS inhibitors (B)</td>
</tr>
<tr>
<td>111</td>
<td><em>Raphanus raphanistrum</em></td>
<td>Wild radish</td>
<td>WA</td>
<td>1997</td>
<td>ALS inhibitors (B)</td>
</tr>
<tr>
<td>112</td>
<td><em>Echium plantagineum</em></td>
<td>Paterson’s curse</td>
<td>WA</td>
<td>1997</td>
<td>ALS inhibitors (B)</td>
</tr>
<tr>
<td>113</td>
<td><em>Raphanus raphanistrum</em></td>
<td>Wild radish</td>
<td>WA</td>
<td>1998</td>
<td><strong>Multiple resistance: two SoA:</strong> ALS inhibitors (B) Carotenoid biosynthesis inhibitors (F)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>114</td>
<td><em>Raphanus raphanistrum</em></td>
<td>Wild radish</td>
<td>WA</td>
<td>1999</td>
<td>Photosystem II inhibitors (C)</td>
</tr>
<tr>
<td>115</td>
<td><em>Raphanus raphanistrum</em></td>
<td>Wild radish</td>
<td>WA</td>
<td>1999</td>
<td>Synthetic auxins (I)</td>
</tr>
<tr>
<td>116</td>
<td><em>Lolium rigidum</em></td>
<td>Wimmera ryegrass</td>
<td>WA</td>
<td>2003</td>
<td>EPSP synthase inhibitors (M)</td>
</tr>
<tr>
<td>117</td>
<td><em>Hordeum glaucum</em></td>
<td>Northern barley grass</td>
<td>WA</td>
<td>2005</td>
<td>ALS inhibitors (B)</td>
</tr>
<tr>
<td>118</td>
<td><em>Bromus rigidus</em></td>
<td>Rigid brome</td>
<td>WA</td>
<td>2005</td>
<td>ACCase inhibitors (A)</td>
</tr>
<tr>
<td>119</td>
<td><em>Echinochloa colona</em></td>
<td>Awnless barnyard grass</td>
<td>WA</td>
<td>2010</td>
<td>EPSP synthase inhibitors (M)</td>
</tr>
<tr>
<td>120</td>
<td><em>Raphanus raphanistrum</em></td>
<td>Wild radish</td>
<td>WA</td>
<td>2010</td>
<td><strong>Multiple resistance: four SoA:</strong> ALS inhibitors (B) Carotenoid biosynthesis inhibitors (F) Synthetic auxins (I) EPSP synthase inhibitors (M)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>121</td>
<td><em>Bromus rigidus</em></td>
<td>Rigid brome</td>
<td>WA</td>
<td>2011</td>
<td>ALS inhibitors (B)</td>
</tr>
<tr>
<td>122</td>
<td><em>Lolium rigidum</em></td>
<td>Wimmera ryegrass</td>
<td>WA</td>
<td>2013</td>
<td><strong>Multiple resistance: two SoA:</strong> Photosystem I electron diverters (L) EPSP synthase inhibitors (M)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>123</td>
<td><em>Ehrharta longiflora</em></td>
<td>Longflowered veldt grass</td>
<td>WA</td>
<td>2014</td>
<td>ACCase inhibitors (A)</td>
</tr>
<tr>
<td>124</td>
<td><em>Bromus rubens</em></td>
<td>Red brome</td>
<td>WA</td>
<td>2014</td>
<td>EPSP synthase inhibitors (M)</td>
</tr>
<tr>
<td>125</td>
<td><em>Vulpia bromoides</em></td>
<td>Squirreltail fescue</td>
<td>WA</td>
<td>2014</td>
<td>Photosystem II inhibitors (C)</td>
</tr>
<tr>
<td>126</td>
<td><em>Tridax procumbens</em></td>
<td>Tridax daisy</td>
<td>WA</td>
<td>2016</td>
<td>EPSP synthase inhibitors (M)</td>
</tr>
</tbody>
</table>


A 2016 report on Australian grain-grower practices found that 64% of growers admit to having resistance with >40% of cropland affected, 17% to having glyphosate resistance and 56% to selective herbicide resistance. This is likely to be an underestimate. Annual ryegrass was by far the most costly resistant weed to manage (Table 2), probably because of its wide distribution in all states except Queensland.)
Feathertop Rhodes grass (*Chloris virgata*) and barnyard grass (*Echinochloa colona*) were the most costly weeds in sorghum-based farming systems.

### Table 2: National ranking of top herbicide-resistant weeds in terms of cost to manage in winter cereal and sorghum crops, 2016 ($/yr).

<table>
<thead>
<tr>
<th>Rank</th>
<th>Winter cereal</th>
<th>Extra herbicide cost</th>
<th>Sorghum</th>
<th>Extra herbicide cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Annual ryegrass</td>
<td>$103.2 million</td>
<td>Feathertop Rhodes grass</td>
<td>$11 million</td>
</tr>
<tr>
<td>2</td>
<td>Wild radish</td>
<td>$19.7 million</td>
<td>Barnyard grass</td>
<td>$810,500</td>
</tr>
<tr>
<td>3</td>
<td>Wild turnip</td>
<td>$7.8 million</td>
<td>Fleabane</td>
<td>$326,000</td>
</tr>
<tr>
<td>4</td>
<td>Wild oats</td>
<td>$6.2 million</td>
<td>Sweet summer grass</td>
<td>$218,400</td>
</tr>
<tr>
<td>5</td>
<td>Barnyard grass</td>
<td>$4.1 million</td>
<td>Ryegrass</td>
<td>$146,600</td>
</tr>
<tr>
<td>6</td>
<td>Indian hedge mustard</td>
<td>$4.1 million</td>
<td>Mint weed</td>
<td>$144,600</td>
</tr>
<tr>
<td>7</td>
<td>Fleabane</td>
<td>$3.6 million</td>
<td>Wild oats</td>
<td>$118.5k</td>
</tr>
<tr>
<td>8</td>
<td>Brome grass</td>
<td>$3.2 million</td>
<td>Thistle species</td>
<td>$106,500</td>
</tr>
<tr>
<td>9</td>
<td>Feathertop Rhodes grass</td>
<td>$2.6 million</td>
<td>Wild radish</td>
<td>$92,500</td>
</tr>
<tr>
<td>10</td>
<td>Phalaris</td>
<td>$2.1 million</td>
<td>Black bindweed/climbing buckwheat</td>
<td>$46,400</td>
</tr>
<tr>
<td>11</td>
<td>Sowthistle/milk thistle</td>
<td>$1.3 million</td>
<td>Indian hedge mustard</td>
<td>$29,900</td>
</tr>
<tr>
<td>12</td>
<td>Windmill grass</td>
<td>$1.2 million</td>
<td>Wild turnip</td>
<td>$27,200</td>
</tr>
<tr>
<td>13</td>
<td>Sweet summer grass</td>
<td>$644,300</td>
<td>Doublegee</td>
<td>$21,400</td>
</tr>
<tr>
<td>14</td>
<td>Mint weed</td>
<td>$636,700</td>
<td>Windmill grass</td>
<td>$13,500</td>
</tr>
<tr>
<td>15</td>
<td>Cape weed</td>
<td>$326,700</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Black bindweed/climbing buckwheat</td>
<td>$233,900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Paterson’s curse/salvation Jane</td>
<td>$212,700</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Barley grass</td>
<td>$203,700</td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Thistle species</td>
<td>$183,600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Mexican poppy</td>
<td>$113,100</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


Paraquat is an important alternative to glyphosate in many circumstances. However, with the increase in use of Group L herbicides that has occurred because of increasing glyphosate resistance and a drop in price, paraquat resistance is becoming more common. It was confirmed in Australia in annual ryegrass in 2010, first in irrigated pasture-seed production fields and then in vineyards. More recently, paraquat resistance has been identified in crowsfoot grass (*Eleusine indica*), blackberry nightshade (*Solanum nigrum*) and cudweed (*Gamochaeta pensylvanica*) from mixed sugarcane–vegetable farming in Queensland, and flaxleaf fleabane (*Conyza bonariensis*) in wine grapes.  

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Resistance to 2,4-D is also on the increase, with four species now resistant, including Indian hedge mustard (Sisymbrium orientale), wild radish, sowthistle (Sonchus oleraceus) and capeweed (Arctotheca calendula). 10

Wild radish has developed resistance to many herbicide MoAs. Many Western Australian growers have only one effective herbicide remaining for wild radish control. Resistance to phenoxy herbicides is widespread in Western Australia and is present in the eastern states. 11

The first cases of 2,4-D resistance in wild radish were reported from South Australia in 2006 and Victoria in 2009. 12

Group I-resistant wild radish was detected at Nyngan, New South Wales, in 2013. 13

Glyphosate resistance

Glyphosate resistance was first documented for annual ryegrass in 1996 in Victoria. Since then, glyphosate resistance has been confirmed in 13 other weed species. Resistance is known in eight grass species and six broadleaf species. Four are winter-growing weed species and 10 non-seasonal or summer-growing weed species. The latter have been selected mainly in chemical fallows. 14

Glyphosate resistance continues to increase across Australian farming systems and anywhere glyphosate is used to control vegetation. Most of the resistant populations are annual ryegrass, followed by barnyard grass, fleabane and sowthistle (Table 3).

Table 3: Glyphosate-resistant weeds in Australia as at December 2016.

<table>
<thead>
<tr>
<th>Weed species</th>
<th>Year first documented</th>
<th>Number of confirmed populations (Dec. 2016)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual ryegrass (Lolium rigidum)</td>
<td>1996</td>
<td>678</td>
</tr>
<tr>
<td>Barnyard grass (Echinochloa colona)</td>
<td>2007</td>
<td>102</td>
</tr>
<tr>
<td>Liverseed grass (Urochloa panicoides)</td>
<td>2008</td>
<td>4</td>
</tr>
<tr>
<td>Fleabane (Conyza bonariensis)</td>
<td>2010</td>
<td>65</td>
</tr>
<tr>
<td>Windmill grass (Chloris truncata)</td>
<td>2010</td>
<td>11</td>
</tr>
<tr>
<td>Wild radish (Raphanus raphanistrum)</td>
<td>2010</td>
<td>2</td>
</tr>
<tr>
<td>Great brome (Bromus diandrus)</td>
<td>2011</td>
<td>5</td>
</tr>
<tr>
<td>Sowthistle (Sonchus oleraceus)</td>
<td>2014</td>
<td>23</td>
</tr>
<tr>
<td>Red brome (Bromus rubens)</td>
<td>2014</td>
<td>1</td>
</tr>
<tr>
<td>Sweet summer grass (Brachiaria eruciformis)</td>
<td>2014</td>
<td>1</td>
</tr>
<tr>
<td>Prickly lettuce (Lactuca serriola)</td>
<td>2014</td>
<td>1</td>
</tr>
<tr>
<td>Feathertop Rhodes grass (Chloris virgata)</td>
<td>2015</td>
<td>4</td>
</tr>
<tr>
<td>Tridax daisy (Tridax procumbens)</td>
<td>2016</td>
<td>1</td>
</tr>
</tbody>
</table>


Although most glyphosate-resistant populations are coming from broadacre cropping, increasing numbers are coming from horticulture, roadsides and fencelines. Glyphosate-resistant populations of annual ryegrass, fleabane and barnyard grass have been found in the following situations (Tables 4–6).

Table 4: Situations in which glyphosate-resistant annual ryegrass has occurred.

<table>
<thead>
<tr>
<th>Situation</th>
<th>No. of sites</th>
<th>State(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broadacre cropping</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical fallow</td>
<td>34</td>
<td>NSW</td>
</tr>
<tr>
<td>Winter grains</td>
<td>393</td>
<td>NSW, Vic., SA, WA</td>
</tr>
<tr>
<td>Summer grains</td>
<td>1</td>
<td>NSW</td>
</tr>
<tr>
<td>Irrigated crops</td>
<td>1</td>
<td>SA</td>
</tr>
<tr>
<td>Horticulture</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tree crops</td>
<td>10</td>
<td>NSW, SA</td>
</tr>
<tr>
<td>Vine crops</td>
<td>25</td>
<td>SA, WA</td>
</tr>
<tr>
<td>Vegetables</td>
<td>2</td>
<td>Vic.</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Driveway</td>
<td>6</td>
<td>NSW, Vic., SA, WA</td>
</tr>
<tr>
<td>Fence line/crop margin</td>
<td>91</td>
<td>NSW, Vic., SA, WA</td>
</tr>
<tr>
<td>Around buildings</td>
<td>2</td>
<td>NSW</td>
</tr>
<tr>
<td>Irrigation channel/drain</td>
<td>14</td>
<td>NSW, Vic., SA</td>
</tr>
<tr>
<td>Airstrip</td>
<td>1</td>
<td>SA</td>
</tr>
<tr>
<td>Railway</td>
<td>2</td>
<td>NSW, WA</td>
</tr>
<tr>
<td>Roadside</td>
<td>95</td>
<td>NSW, SA, WA</td>
</tr>
<tr>
<td>Pasture</td>
<td>1</td>
<td>WA</td>
</tr>
</tbody>
</table>

Table 5: Situations in which glyphosate-resistant fleabane has occurred.

<table>
<thead>
<tr>
<th>Situation</th>
<th>No. of sites</th>
<th>State(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broadacre cropping</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical fallow</td>
<td>16</td>
<td>NSW, Qld</td>
</tr>
<tr>
<td>Horticulture</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vineyard</td>
<td>1</td>
<td>SA</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Around buildings</td>
<td>1</td>
<td>NSW</td>
</tr>
<tr>
<td>Irrigation channel/drain</td>
<td>10</td>
<td>NSW</td>
</tr>
<tr>
<td>Railway</td>
<td>3</td>
<td>NSW</td>
</tr>
<tr>
<td>Roadside</td>
<td>27</td>
<td>SA, NSW, Qld</td>
</tr>
</tbody>
</table>

Table 6: Situations in which glyphosate-resistant awnless barnyard grass has occurred.

<table>
<thead>
<tr>
<th>Situation</th>
<th>No. of sites</th>
<th>State(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broadacre cropping</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemical fallow</td>
<td>97</td>
<td>NSW, Qld, WA</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Around buildings</td>
<td>1</td>
<td>NSW</td>
</tr>
<tr>
<td>Irrigation channel/drain</td>
<td>2</td>
<td>NSW, Qld</td>
</tr>
</tbody>
</table>

Management practices can increase or decrease the risk of glyphosate resistance developing on-farm (see Table 7, devised by the Australian Glyphosate Sustainability Working Group with minor modifications for the Queensland cropping region).  

Table 7: Balancing the risk of weeds developing glyphosate resistance.

<table>
<thead>
<tr>
<th>Risk increasing</th>
<th>Risk decreasing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous reliance on glyphosate pre-seeding</td>
<td>Double-knock technique</td>
</tr>
<tr>
<td>Lack of tillage</td>
<td>Strategic use of alternative knockdown groups</td>
</tr>
<tr>
<td>Lack of effective in-crop weed control</td>
<td>Full-disturbance cultivation at sowing</td>
</tr>
<tr>
<td>Inter-row glyphosate use (unregistered use in all crops except cotton)</td>
<td>Effective in-crop weed control</td>
</tr>
<tr>
<td>Frequent glyphosate-based chemical fallow</td>
<td>Use of alternative herbicide groups or tillage for inter-row and fallow weed control</td>
</tr>
<tr>
<td>High weed numbers</td>
<td>Non-herbicide practices for weed-seed kill</td>
</tr>
<tr>
<td>Over-reliance on glyphosate-resistant crops</td>
<td>Applying stewardship plans when growing glyphosate-resistant crops</td>
</tr>
<tr>
<td>Pre-harvest desiccation with glyphosate</td>
<td>Farm hygiene to prevent resistance movement</td>
</tr>
</tbody>
</table>

In 2013–14, two populations of sowthistle from northern New South Wales were determined to be glyphosate-resistant. Since then, the Queensland Department of Agriculture and Fisheries has been leading a glyphosate-resistance survey of sowthistle across the northern cropping region, in collaboration with the NSW Department of Primary Industries (NSW DPI) and grower solutions groups including the Northern Grower Alliance (NGA) and the Grain Orana Alliance (GOA).

This survey has confirmed an additional 21 resistant populations from the Liverpool Plains in New South Wales to central Queensland.

The survey indicated that many populations remain susceptible to glyphosate when treated at the small rosette stage and according to label recommendations. 17

3.1.1 Resistance in the northern region

Queensland and northern New South Wales

Herbicide resistance is an increasing threat for growers and agronomists across the northern grains region. As of early 2017, there were 20 weed species in northern New South Wales and Queensland with resistance to one or more herbicides (Table 8). Across these weeds, there was resistance to six different MoAs. 18,19
Table 8: List of weed species with herbicide-resistant populations present in the northern grains region, and the Modes of Action to which resistance has developed.

<table>
<thead>
<tr>
<th>Weed species</th>
<th>Common name(s)</th>
<th>Herbicide Mode of Action Group(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avena spp.</td>
<td>Wild oats, black oats</td>
<td>A, B, Z</td>
</tr>
<tr>
<td>Chloris truncata</td>
<td>Windmill grass</td>
<td>M</td>
</tr>
<tr>
<td>Chloris virgata</td>
<td>Feathertop Rhodes grass</td>
<td>M</td>
</tr>
<tr>
<td>Conyza bonariensis</td>
<td>Flaxleaf fleabane</td>
<td>M</td>
</tr>
<tr>
<td>Conyza sumatrensis</td>
<td>Tall fleabane</td>
<td>M</td>
</tr>
<tr>
<td>Echinochloa colona</td>
<td>Barnyard grass</td>
<td>C, M</td>
</tr>
<tr>
<td>Eleusine indica</td>
<td>Crowsfoot grass</td>
<td>L</td>
</tr>
<tr>
<td>Fallopia convolvulus</td>
<td>Black bindweed, climbing buckwheat</td>
<td>B</td>
</tr>
<tr>
<td>Gamochaeta pensylvanica</td>
<td>Cudweed</td>
<td>L</td>
</tr>
<tr>
<td>Lolium rigidum</td>
<td>Annual ryegrass</td>
<td>A, B, J, M</td>
</tr>
<tr>
<td>Mitracarpus hirtus</td>
<td>Square weed</td>
<td>L</td>
</tr>
<tr>
<td>Phalaris paradoxa</td>
<td>Paradoxa grass, phalaris</td>
<td>A, B</td>
</tr>
<tr>
<td>Rapistrum rugosum</td>
<td>Turnip weed</td>
<td>B</td>
</tr>
<tr>
<td>Raphanus raphanistum</td>
<td>Wild radish</td>
<td>B, I</td>
</tr>
<tr>
<td>Sinapis arvensis</td>
<td>Charlock</td>
<td>B</td>
</tr>
<tr>
<td>Sisymbrium orientale</td>
<td>Indian hedge mustard</td>
<td>B</td>
</tr>
<tr>
<td>Sisymbrium thellungi</td>
<td>African turnip weed</td>
<td>B</td>
</tr>
<tr>
<td>Solanum nigrum</td>
<td>Blackberry nightshade</td>
<td>L</td>
</tr>
<tr>
<td>Sonchus oleraceus</td>
<td>Sowthistle, milkthistle</td>
<td>B, M</td>
</tr>
<tr>
<td>Urochloa panicoides</td>
<td>Liverseed grass</td>
<td>M</td>
</tr>
</tbody>
</table>

In southern Queensland, seven weeds are confirmed resistant to Group A, B or C herbicides (Table 9). A further five weeds are confirmed resistant to glyphosate.

In central Queensland, the first case of herbicide resistance was confirmed in 2014, with a population of sweet summer grass found to be resistant to glyphosate. This is now joined by glyphosate-resistant sowthistle.

Liverseed grass (Urochloa panicoides) and wild oats also present a risk of developing resistance to Group M (glyphosate) herbicides (see Table 10). Glyphosate-resistant liverseed grass is currently restricted to northern New South Wales.

Other broadleaf and grass weeds present a risk of developing resistance, depending on weed numbers and management practices used.  

---

Table 9: Confirmed resistant weeds in southern Queensland.

<table>
<thead>
<tr>
<th>Weed</th>
<th>Herbicide MoA Group</th>
<th>Extent of resistance</th>
<th>Future risk</th>
<th>Detrimental impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wild oats</td>
<td>A (e.g. Topik®, Wildcat®)</td>
<td>Spread across the main wheat-growing areas</td>
<td>Areas growing predominantly winter crops</td>
<td>Very high</td>
</tr>
<tr>
<td>African turnip weed</td>
<td>B (e.g. Glean®, Ally®)</td>
<td>Spread across the main wheat-growing area</td>
<td>Areas growing predominantly winter crops</td>
<td>Moderate</td>
</tr>
<tr>
<td>Black bindweed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Common sowthistle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indian hedge mustard</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turnip weed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liverseed grass</td>
<td>C (e.g. atrazine)</td>
<td>A few paddocks in eastern Darling Downs</td>
<td>Areas predominantly growing sorghum</td>
<td>High</td>
</tr>
<tr>
<td>Barnyard grass</td>
<td>M (glyphosate)</td>
<td>Eastern and western Downs</td>
<td>Summer fallows</td>
<td>Very high</td>
</tr>
<tr>
<td>Flaxleaf fleabane</td>
<td>M</td>
<td>Eastern and western Downs</td>
<td>Fallows</td>
<td>Very high</td>
</tr>
<tr>
<td>Common sowthistle</td>
<td>M, B</td>
<td>Eastern and western Downs</td>
<td>Fallows</td>
<td>Very high</td>
</tr>
</tbody>
</table>

Table 10: Potential new resistant weeds in central and southern Queensland.

<table>
<thead>
<tr>
<th>Weed</th>
<th>Herbicide MoA Group</th>
<th>Future risk</th>
<th>Detrimental impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wild oats</td>
<td>M</td>
<td>No-till and minimum-till systems (only southern Qld)</td>
<td>High</td>
</tr>
<tr>
<td>Barnyard grass</td>
<td>C, L (e.g. paraquat)</td>
<td>Areas growing predominantly sorghum Fallows All summer crops</td>
<td>High High High</td>
</tr>
<tr>
<td>Parthenium</td>
<td>B</td>
<td>Areas growing predominantly winter crops</td>
<td>High</td>
</tr>
<tr>
<td>Other Brassica weeds</td>
<td>B</td>
<td>Areas growing predominantly winter crops</td>
<td>Moderate</td>
</tr>
<tr>
<td>Featherhead Rhodes grass</td>
<td>A</td>
<td>Used in fallow, often under poor spray conditions with no double-knock with paraquat</td>
<td>Very high</td>
</tr>
<tr>
<td></td>
<td>L</td>
<td>Often used alone as a spot spray treatment or applied with a Weed-Seeker® or Weed-IT®</td>
<td>Very high</td>
</tr>
</tbody>
</table>

Central-western New South Wales

Grain Orana Alliance (GOA) tested 130 annual ryegrass and 84 wild oat populations across the central-western New South Wales region over the 2013 and 2014 seasons. Seed samples were supplied by growers and advisers. Samples were taken from cropping paddocks with no stipulation of their suspected resistance status. That is that they could be taken from paddocks regardless of whether they were suspected resistant or not.

Results are presented in Tables 11–14 below. Testing revealed that herbicide resistance was widespread and that the vast majority of the samples submitted had resistance to multiple herbicides. In several cases, the multiple resistance was such that only a few potentially effective herbicide options were left that might control those weeds.

The survey was very helpful in identifying some of the herbicide groups that are most challenged in terms of efficacy. The survey also serves as a warning to growers regarding what many have thought to be ‘safe’ and ‘effective’ herbicide options (e.g. Select®, atrazine, trifluralin and glyphosate). There are clear signs that resistance to these products is present in the region. 21

Testing also revealed the complexity of multiple resistances. The lack of clear patterns related to management makes it difficult to assume that a weed population is either resistant or susceptible. Testing must therefore be conducted to determine which herbicides are still effective. 22

Riverina and southern New South Wales

Herbicide resistance in annual ryegrass and common sowthistle in the Riverina region of New South Wales has increased significantly in recent years.

A project initiated by NSW DPI, and managed by Ag Grow Agronomy in 2012, evaluated ryegrass and sowthistle samples taken from both known resistant and non-resistant populations. All (i.e. 100%) of the ryegrass samples and 22% of the sowthistle samples were resistant to at least one herbicide. Multiple resistance in ryegrass was common.

When predicting ryegrass resistance, growers and advisers were accurate 74% of the time. Accuracy reduced to 65% for post-emergent herbicides.

Cross-resistance between Logran® and Hussar® in ryegrass was lower than expected considering that both are Group B sulfonylurea herbicides. This has raised some questions for possible future research.

No-till continuous cropping rotations hosted higher resistance levels and often resistance to more herbicides than less intensive rotations that included pasture. However, in many cases, samples from paddocks that have had minimal herbicide applications showed resistance to multiple herbicides. 23

In 2015, annual ryegrass from southern New South Wales was confirmed resistant to triallate (Group J) with cross-resistance to prosulfocarb (Boxer Gold®, Group J).

Table 11: Sample populations of annual ryegrass and incidence of multiple resistance to the herbicide Mode of Action (MoA) groups or subgroups, tested in 2014, central-western NSW.

<table>
<thead>
<tr>
<th>No. of herbicide MoA groups or subgroups with demonstrated resistance</th>
<th>No. of samples</th>
<th>Per cent of samples submitted</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>14</td>
<td>27</td>
</tr>
<tr>
<td>6</td>
<td>12</td>
<td>24</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>Totals</td>
<td>51</td>
<td>100</td>
</tr>
</tbody>
</table>

Herbicides groups and subgroups considered were ‘fops’, ‘dims’ (Select® only), ‘dens’, sulfonylureas, imidazolinones, triazines and glycines. A weed resistant to fops, dims and dens (all Group A) would be considered resistant to these groups or subgroups; these are considered subgroups of Group A because of common acceptance that differential levels of control can often be expected when using these herbicides. Similarly, Group B herbicides are in two subgroups, sulfonylureas and imidazolinones.

Table 12: Number of annual ryegrass samples demonstrating resistance to the various herbicides and rates, central-western NSW.

<table>
<thead>
<tr>
<th>Herbicide and rate</th>
<th>No of samples with ≥10% survival</th>
<th>Per cent of samples with ≥10% survival</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trifluralin, 2000 mL/ha</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Verdict®, 100 mL/ha</td>
<td>44</td>
<td>86</td>
</tr>
<tr>
<td>Select®, 350 mL/ha</td>
<td>31</td>
<td>61</td>
</tr>
<tr>
<td>Select®, 500 mL/ha</td>
<td>13</td>
<td>26</td>
</tr>
<tr>
<td>Factor®, 180 g/ha</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td>Axial®, 300 mL/ha</td>
<td>39</td>
<td>77</td>
</tr>
<tr>
<td>Logran® 750, 35 g/ha</td>
<td>46</td>
<td>90</td>
</tr>
<tr>
<td>Hussar® OD, 100 mL/ha</td>
<td>44</td>
<td>86</td>
</tr>
<tr>
<td>Intervix®, 750 mL/ha</td>
<td>30</td>
<td>59</td>
</tr>
<tr>
<td>Atrazine 900 WG, 2000 g/ha</td>
<td>19</td>
<td>37</td>
</tr>
<tr>
<td>Glyphosate 540, 1000 mL/ha</td>
<td>29</td>
<td>57</td>
</tr>
<tr>
<td>Glyphosate 540, 1500 mL/ha</td>
<td>9</td>
<td>18</td>
</tr>
<tr>
<td>Glyphosate 540, 2000 mL/ha</td>
<td>4</td>
<td>8</td>
</tr>
</tbody>
</table>
Table 13: Sample populations of wild oats and incidence of multiple resistance to the herbicide Mode of Action (MoA) groups or subgroups tested in 2014, central-western NSW.

<table>
<thead>
<tr>
<th>No. of herbicide MoA groups or subgroups with demonstrated resistance</th>
<th>No. of samples</th>
<th>Per cent of samples submitted</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>29</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>21</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>17</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td>Totals</td>
<td>42</td>
<td>100</td>
</tr>
</tbody>
</table>

Herbicides groups and subgroups tested were fops (Topik®, Verdict®), diis, dens, sulfonylureas, Group Z.

Table 14: Number of wild oat samples demonstrating resistance to the various herbicides and rates tested, central-western NSW.

<table>
<thead>
<tr>
<th>Herbicide and rate</th>
<th>No. of samples tested</th>
<th>No. of samples with ≥10% resistance</th>
<th>Per cent of samples with ≥10% resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topik®, 100 mL/ha</td>
<td>42</td>
<td>36</td>
<td>86</td>
</tr>
<tr>
<td>Topik®, 210 mL/ha</td>
<td>40</td>
<td>27</td>
<td>68</td>
</tr>
<tr>
<td>Verdict®, 100 mL/ha</td>
<td>42</td>
<td>20</td>
<td>48</td>
</tr>
<tr>
<td>Select®, 350 mL/ha</td>
<td>42</td>
<td>8</td>
<td>19</td>
</tr>
<tr>
<td>Axial®, 200 mL/ha</td>
<td>42</td>
<td>14</td>
<td>33</td>
</tr>
<tr>
<td>Atlantis®, 330 mL/ha</td>
<td>42</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Flamprop-m-methyl, 1.8 L/ha</td>
<td>42</td>
<td>29</td>
<td>69</td>
</tr>
</tbody>
</table>


The identification of resistance to several key products such as the ‘fop’ and Group B herbicides in these GOA surveys is no surprise. Alarming, however, the testing has highlighted some cases of resistance to ‘less used’ products—largely thought to be still effective—that were forming a key backstop for control of annual ryegrass and wild oats.

Despite lower levels of use of atrazine and trifluralin, 19 populations (37%) of annual ryegrass demonstrated resistance to atrazine. Resistance to trifluralin was found in only one population of annual ryegrass in the 2014 survey, similar to the findings in 2013.

Resistance to Intervix® (Group B ‘imi’), used in Clearfield® canola, was shown in 59% of the annual ryegrass samples, largely due to cross-resistance from widespread Group B sulfonylurea use.

For many farmers in the region, Select® (clethodim) is the only reliable in-crop selective herbicide available and a key tool for managing annual ryegrass. Resistance is therefore a concern; >60% of annual ryegrass samples were resistant at the lower application rate of 350 mL/ha. One population was also resistant to Verdict®, Axial®, Logran® and Hussar®. Increasing the application rate to 500 mL/ha still saw 25% of samples resistant.

Flamprop-m-methyl (Group Z) is an alternative herbicide for the control of wild oats. However, 69% of the survey populations were resistant, and also resistant to Topik®
(clodinafop). It has been known since 2005 that clodinafop resistance in wild oats often confers cross-resistance to flamprop-m-methyl. 24

Herbicides play a pivotal role in current minimum-till or no-till farming systems. Possibly the most important product in the northern farming region is glyphosate, and this survey has shown significant levels of resistance, with 57% of populations resistant at 1 L/ha, 18% at 1.5 L/ha and 8% at 2 L/ha, applied under laboratory conditions.

Growers and advisers submitted weed seed samples and 130 annual ryegrass and 84 wild oat populations were tested across Central West NSW over two seasons.

Lower levels of resistance were generally detected in populations that had received fewer (six to eight) applications, whereas higher levels were recorded where >100 applications were reported. Glyphosate is invaluable in the control of weeds in the region’s fallow systems, and these systems are essential for conserving out-of-season rainfall to achieve profitable crop yields. Glyphosate is also important for managing pre-planting flushes of weeds, potentially the largest germination of winter weeds. Loss of efficacy of this herbicide will seriously challenge the sustainability of profitable farming systems. 25

3.1.2 Resistance in the southern region

Weed surveys across the southern region have shown increasing levels of resistance to clethodim in annual ryegrass. This is important because clethodim is the last Group A herbicide to provide effective control of ‘fop’-resistant annual ryegrass and is the final control available for late-emerging ryegrass in canola and pulses.

Although levels of resistance to the range of pre-emergent herbicides remain low, these herbicides give unsatisfactory levels of control when used alone and not followed by a post-emergent grass herbicide.

Resistance in annual ryegrass is generally greater in higher rainfall southern areas, which have longer growing seasons and tend to be more heavily cropped. Annual ryegrass in these areas is resistant to all post-emergent herbicides.

Eyre Peninsula

The Eyre Peninsula of South Australia has seen a steady increase in trifluralin resistance in annual ryegrass, whereas levels of resistance to other herbicides have plateaued except for several new populations of triallate (Group J) resistance with some cross-resistance to prosulfocarb (Boxer® Gold) (Table 15).

Table 15: Proportion of annual ryegrass populations tested that were resistant to herbicides in the Eyre Peninsula survey, 2014 (>20% of individuals survive the herbicide).

<table>
<thead>
<tr>
<th>Herbicide</th>
<th>Mode of Action Group</th>
<th>Southern Eyre Peninsula</th>
<th>Northern Eyre Peninsula</th>
<th>Total Populations resistant (% tested)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trifluralin</td>
<td>D</td>
<td>51</td>
<td>10</td>
<td>34</td>
</tr>
<tr>
<td>Propyzamide</td>
<td>D</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sakura®</td>
<td>K</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Triallate</td>
<td>J</td>
<td>3</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Boxer Gold®</td>
<td>J + K</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Diclofop-methyl</td>
<td>A</td>
<td>73</td>
<td>10</td>
<td>47</td>
</tr>
<tr>
<td>Clethodim</td>
<td>A</td>
<td>7</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>Pinoxaden</td>
<td>A</td>
<td>32</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td>Chlorsulfuron</td>
<td>B</td>
<td>85</td>
<td>75</td>
<td>80</td>
</tr>
<tr>
<td>Intervix®</td>
<td>B</td>
<td>53</td>
<td>39</td>
<td>47</td>
</tr>
<tr>
<td>Glyphosate</td>
<td>M</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Half of the brome grass (*Bromus* spp.) populations tested were resistant to Group B sulfonylureas but not to ‘imis’, whereas <5% of the populations were resistant to Group A ‘fops’.

Barley grass (*Hordeum* spp.) samples collected in 2014 showed <5% of populations resistant to Group A ‘fops’ and 16% resistant to Group B sulfonylureas. Wild oats (*Avena* spp.) had 4% of populations resistant to clodinafop (Group A) and 3% resistant to Group B sulfonylureas.

Indian hedge mustard was found resistant to multiple herbicides, and sowthistle to Group B sulfonylureas (Table 16).

Table 16: Proportion of Indian hedge mustard and sowthistle populations resistant to herbicides in the Eyre Peninsula survey, 2014 (>20% of individuals survive the herbicide).

<table>
<thead>
<tr>
<th>Herbicide</th>
<th>Mode of Action Group</th>
<th>Indian hedge mustard</th>
<th>Sowthistle</th>
<th>Populations resistant (% tested)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorsulfuron</td>
<td>B, sulfonylurea</td>
<td>64</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>Metosulam</td>
<td>B, sulfonamide</td>
<td>74</td>
<td>Not tested</td>
<td></td>
</tr>
<tr>
<td>Intervix®</td>
<td>B, imidazolinone</td>
<td>14</td>
<td>Not tested</td>
<td></td>
</tr>
<tr>
<td>Diflufenican</td>
<td>F</td>
<td>36</td>
<td>Not tested</td>
<td></td>
</tr>
<tr>
<td>2,4-D</td>
<td>I</td>
<td>7</td>
<td>Not tested</td>
<td></td>
</tr>
<tr>
<td>Atrazine</td>
<td>C</td>
<td>7</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Glyphosate</td>
<td>M</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
South-east South Australia

In 2014, 122 paddocks in South East South Australia were surveyed for herbicide resistance. Very high levels of resistance were detected in annual ryegrass to trifluralin (Group D; 78% of samples with >20% survival) and to Groups A (diclofop-methyl, 90%; pinoxaden, 80%) and Group B (chlorsulfuron, 70%; Intervix®, 72%) herbicides. Of the fields sampled, 16% showed resistance to glyphosate (Group M). 26

Wimmera and Mallee

A resistance survey conducted in the Wimmera and Mallee regions in 2015 found high levels of resistance to trifluralin (Group D) and Groups A and B herbicides, with glyphosate resistance levels high enough to be found in a random survey (Table 17). No resistance was found to any other pre-emergent herbicides.

Table 17: Extent of herbicide resistance in annual ryegrass, Wimmera and Mallee, 2015 (>20% of individuals survive the herbicide).

<table>
<thead>
<tr>
<th>Herbicides tested</th>
<th>Mode of Action Group</th>
<th>Percentage of annual ryegrass populations resistant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Wimmera</td>
</tr>
<tr>
<td>Trifluralin</td>
<td>D</td>
<td>36</td>
</tr>
<tr>
<td>Propyzamide</td>
<td>D</td>
<td>0</td>
</tr>
<tr>
<td>Boxer Gold®</td>
<td>J + K</td>
<td>0</td>
</tr>
<tr>
<td>Sakura®</td>
<td>K</td>
<td>0</td>
</tr>
<tr>
<td>Diclofop-methyl</td>
<td>A</td>
<td>80</td>
</tr>
<tr>
<td>Sulfometuron</td>
<td>B</td>
<td>53</td>
</tr>
<tr>
<td>Intervix®</td>
<td>B</td>
<td>21</td>
</tr>
<tr>
<td>Pinoxaden</td>
<td>A</td>
<td>46</td>
</tr>
<tr>
<td>Clethodim</td>
<td>A</td>
<td>10</td>
</tr>
<tr>
<td>Glyphosate</td>
<td>M</td>
<td>9</td>
</tr>
</tbody>
</table>

Southern Victoria

During 2014, a survey was conducted in south-western Victoria (Table 18). 27 Although trifluralin (Group D) resistance in ryegrass remained low, 10% of samples were resistant to Group J (triallate). Incidence of resistance to the post-emergent herbicides chlorsulfuron (Group B) and diclofop-methyl (Group A) was very high; however, other classes of those MoA groups were still largely effective.

Of wild radish samples, 43% were resistant to chlorsulfuron (Group B) and 7% were resistant to 2,4-D (Group I).

Table 18: Incidence of herbicide resistance in south-western Victoria as determined by a random weed survey of 120 paddocks in 2014 by the University of Adelaide. Data represent the percentage of samples (one sample represents one paddock) where ≥20% survival was recorded in a pot trial. Each herbicide was applied at the field rate with the recommended adjuvants.

<table>
<thead>
<tr>
<th>Pre-emergent herbicide (MoA Group)</th>
<th>Trifluralin (D)</th>
<th>Propyzamide (D)</th>
<th>Triallate (J)</th>
<th>Boxer® Gold (J + K)</th>
<th>Sakura® (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ryegrass</td>
<td>2</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Post-emergent herbicide (MoA Group)</th>
<th>Chlorsulfuron (B)</th>
<th>Intervix® (B)</th>
<th>Diclofop-methyl (A)</th>
<th>Pinoxaden (A)</th>
<th>Clethodim (A) 250 mL/ha</th>
<th>Clethodim (A) 500 mL/ha</th>
<th>Glyphosate (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ryegrass</td>
<td>96</td>
<td>33</td>
<td>86</td>
<td>53</td>
<td>6</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Wild radish</td>
<td>43</td>
<td>0</td>
<td>7</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


Tasmania

In 2010, a random survey was conducted of Tasmanian cropping areas by collecting annual ryegrass, wild oats, giant brome and barley grass. 28 Ryegrass-resistance frequencies were:
- Group A ‘fops’, 18%
- Group A ‘dims’, 1%
- Group B sulfonylureas, 24%
- Group D (trifluralin), 1%

Of the ryegrass samples tested against four herbicide groups (A, B, C, D), 64% were susceptible to all herbicides, 27% resistant to one herbicide only, 7% to two herbicide MoA groups, and one sample was resistant to three herbicide groups.

Two wild oat and one barley grass sample were found resistant to Group A ‘fops’.

In a 2015 survey of wild radish populations, two of the 24 samples collected were resistant to Group B sulfonylureas and six were resistant to Group B ‘imis’ (Table 19). At 37%, resistance to Group B ‘imi’ herbicides was much higher than the level found in New South Wales at that time. Two populations were resistant to 2,4-D and two were developing resistance. 29 Most of the wild radish populations were collected in northern Tasmania, most likely due to a larger range of broadleaf crops being grown, making wild radish much harder to control than in the cereal-based farming systems of south-eastern Tasmania.

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Table 19: Herbicide resistance in Tasmanian wild radish populations, 2015.

<table>
<thead>
<tr>
<th>Herbicide</th>
<th>Number of populations tested</th>
<th>Resistant (&gt;20% survival)</th>
<th>Developing resistance (10–19% survival)</th>
<th>Total resistant (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorsulfuron (B)</td>
<td>24</td>
<td>2</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>Imazamox + imazapyr (B)</td>
<td>19</td>
<td>6</td>
<td>1</td>
<td>37</td>
</tr>
<tr>
<td>Atrazine (C)</td>
<td>20</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Diflufenican (F)</td>
<td>21</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2,4-D (I)</td>
<td>23</td>
<td>2</td>
<td>2</td>
<td>17</td>
</tr>
<tr>
<td>Glyphosate (M)</td>
<td>19</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>


3.1.3 Resistance in the western region

Herbicide resistance continues to increase in Western Australia, with multiple-resistant populations of both annual ryegrass and wild radish becoming widespread. 30, 31

Several surveys have been conducted by AHRI in the Western Australian grainbelt to determine the frequency and extent of herbicide resistance in wild radish in cropping regions.

In 2010, AHRI conducted a random to assess the herbicide-resistance status of five important weed species to commonly used herbicides in the Western Australian wheatbelt. The survey team travelled from Binnu in the north of the state to Esperance in the south, visiting 466 cropping paddocks and collecting seed of 362 ryegrass, 96 wild radish, 128 wild oats, 47 barley grass and 91 brome grass populations.

Annual ryegrass

The extensive and long-term use of Group A and B herbicides is increasing herbicide resistance to those MoA groups. The 2010 survey found 95% of annual ryegrass of populations in Western Australia resistant to two or more MoAs. Table 20 shows significant increases in resistance in the 7 years between surveys taken in 2003 and 2010.

Table 20: Increase in herbicide resistance in annual ryegrass in Western Australia since the 2003 survey

<table>
<thead>
<tr>
<th>Herbicide</th>
<th>Increase since 2003 (%)</th>
<th>2010 survey: populations with resistant plants (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diclofop-methyl</td>
<td>28</td>
<td>96</td>
</tr>
<tr>
<td>Clethodim (250 mL/ha)</td>
<td>57</td>
<td>65</td>
</tr>
<tr>
<td>Clethodim (500 mL/ha)</td>
<td>Not tested</td>
<td>42</td>
</tr>
<tr>
<td>Sulfometuron</td>
<td>10</td>
<td>98</td>
</tr>
<tr>
<td>Trifluralin</td>
<td>3</td>
<td>27</td>
</tr>
<tr>
<td>Atrazine</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Glyphosate</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Paraquat</td>
<td>Not tested</td>
<td>0</td>
</tr>
</tbody>
</table>


**Wild radish**

Wild radish seedlings were screened for resistance to the commonly used herbicides including chlorsulfuron, imazamox + imazapyr, 2,4-D amine, diflufenican, atrazine, pyrasulfotole + bromoxynil and glyphosate at recommended field rates.

The major findings included:

- Resistance to chlorsulfuron (Glean®, Group B) was present in 84% of populations, a 30% increase since the 2003 survey.
- Resistance to imazamox + imazapyr (Intervix®, Group B) occurred in half of the populations.
- Resistance to 2,4-D amine (Group I) occurred in 76% of populations, mostly in the northern half of the wheatbelt.
- Resistance to diflufenican (Brodal®, Group F) was present in half of the populations.
- Only one population was resistant to atrazine (Group C).
- As in 2003, no populations were found with resistance to pyrasulfotole + bromoxynil (Velocity®, Groups H and C) or glyphosate. 32

**Other weeds**

Most of the 128 wild oat populations were collected in the southern half of the wheatbelt, with resistance to diclofop-methyl widespread. Resistance to other Group A herbicides was highly variable and no resistance to glyphosate or paraquat was detected. Groups B, J and Z were not tested. This reflects the 2005 survey in which >70% of the populations were resistant to diclofop-methyl with a further 23% resistant to fenoxaprop and sethoxydim.

Three of the 47 barley grass populations were resistant to Group B sulfonylureas, two having cross-resistance to Group B ‘imis’. Most of the resistant barley grass populations were collected in the southern wheatbelt.

Of the 91 brome grass populations, 13%, mostly from the northern half of the wheat belt, were resistant to Group B sulfonylureas, with one population resistant to Group A.

**Glyphosate resistance**

In 2013, the Department of Agriculture & Food WA conducted a targeted survey of weedy paddocks across the southern half of the wheatbelt looking for glyphosate-resistant annual ryegrass. Over 40% of the paddocks sampled contained some level of resistance. Many growers were surprised that they had glyphosate resistance, probably because low-level resistance is difficult to observe in the paddock without conducting testing. 33

In 2014, a population of red brome (Bromus rubens) was confirmed resistant to glyphosate in the central wheatbelt of Western Australia. This was the first red brome population to be confirmed resistant to glyphosate anywhere in the world and the third glyphosate-resistant grass weed species found in Western Australia. 34

**3.2 Mechanisms of resistance**

Mechanisms of herbicide resistance are divided into two categories: target-site and non-target-site.
3.2.1 Target-site resistance mechanisms

Target-site mechanisms involve a change to the protein that binds the herbicide, resulting in a lack of inhibition of the biochemical pathway in the plant.

The first and most straightforward is where a mutation within the target protein reduces or eliminates binding of the herbicide. This is the classic target-site mutation and is typically perceived as providing virtual immunity to the herbicide. However, that is not always the case; it is possible to have weak target-site mutations as well as strong target-site mutations. Target-site mutations arise through single point mutations in the DNA that change an amino acid in the protein. This changed amino acid may either remove a bond required for binding the herbicide or change the shape of the binding pocket.

Target-site mutations are common in weeds with resistance to Group A, Group B and Group C herbicides, but they also occur in resistance to Group D and Group M herbicides. With target-site resistance, cross-resistance to other herbicides of the same herbicide MoA is common.

For most target sites, more than one possible mutation can provide resistance to herbicides. In many cases, different mutations give different levels of resistance and patterns of cross-resistance. For example, resistance selected by sulfonylurea herbicides may not result in resistance to the imidazolinone herbicides (both Group B). Cross-resistance to imidazolinone herbicides occurs approximately 30% of the time with broadleaf weeds and 50% of the time with grass weeds. However, this varies between species.

There are eight different amino acids within the ALS protein where mutations are known to result in resistance to Group B herbicides. Of these, four give strong resistance to sulfonylurea herbicides and six give strong resistance to imidazolinone herbicides. Therefore, only some of the mutations provide resistance to both classes of herbicides. This is because the different classes of herbicides bind differently in the binding pocket, so different mutations may affect only one or both types of herbicide.

A different situation has arisen with Group A herbicides. For ACCase, there are seven amino acids within the protein where mutations are known to provide resistance to herbicides. Most of these provide resistance to the aryloxyphenoxypropionate ('fop') herbicides, but only three provide any resistance to clethodim, with only one giving high-level resistance on its own. Therefore, most target-site mutations selected by fop herbicides can be controlled by clethodim. This allowed growers in southern Australia to exploit fop herbicides first in the control of annual ryegrass, and after those herbicides failed, they used clethodim. Once clethodim started to fail, higher rates of this herbicide were used, because only one mutation provided high-level resistance to clethodim.

The second type of target-site resistance occurs when there are many more copies of the target site than would normally be present. This is called gene amplification. In this type of resistance, the extra target sites act like a sponge, soaking up the herbicide. So far, this mechanism has been seen only in glyphosate-resistant weeds, such as giant brome in Australia and Palmer amaranth (Amaranthus palmeri) in the USA. If this type of mechanism were to occur for another herbicide target site, it would be expected to provide resistance to every herbicide in that MoA group.

3.2.2 Non-target-site resistance mechanisms

Non-target-site resistance mechanisms permit plants to survive application of the herbicide by preventing sufficient herbicide from reaching the target site. The weed may be initially affected by the herbicide application, but will survive and set seed.

The first and most common type of non-target-site resistance occurs through increased herbicide detoxification. With this resistance mechanism, breakdown of the herbicide inside the plant is more rapid; therefore, less of the active herbicide reaches the target site to kill the plant. Such enhanced metabolism is typically
observed for herbicides that can be used selectively in the crop, such as Groups A, B, C, D and I.

The exact nature of the mutation that leads to resistance through enhanced metabolism has not been determined. However, evidence points to the increased activity of several enzymes, rather than a single enzyme. Enhanced metabolism frequently leads to cross-resistance to herbicides of different MoA groups, which complicates management of resistance with herbicides because cross-resistance patterns tend to be highly variable and unpredictable. This indicates that several types of enhanced herbicide detoxification are occurring.

A variant on herbicide detoxification is reduced activation of the herbicide. Several herbicides are applied as pro-herbicides and rely on the plant metabolising them to the active compound. If the plant fails to do this, the herbicide will not work. Reduced activation has been observed in triallate resistance in Canada, but has not been found in Australia.

The second non-target-site mechanism involves changes to the translocation of herbicides within the plant. The herbicide becomes trapped in the leaf tips and reduced amounts reach the target sites. This mechanism is common in weeds resistant to Group L and Group M herbicides, but has also been seen in weeds resistant to Group A herbicides.

A plant can reduce the translocation of herbicides by several means. The main process is by pumping the herbicide into the cell vacuole. Because this involves specific transporters for the herbicide, resistance usually occurs to a single herbicide only. However, with paraquat, cross-resistance to diquat always occurs.

Reduced translocation can also occur if the herbicide is trapped in tissues that are then shed from the plant. This ‘rapid necrosis’ resistance resembles the plant response to pathogen attack, but on a massive scale where the whole leaves rapidly die and fall off, taking the herbicide with them. This type of resistance has been observed to glyphosate in other countries, but not in Australia.

Two other mechanisms of non-target-site resistance are theoretically possible, but have not been well documented. Reduced absorption of the herbicide into the plant will lower the concentration of herbicide at the target site. This is possible only for herbicides that are absorbed solely through leaf tissue (foliar-absorbed). The other mechanism is plant avoidance of the detrimental effect of the herbicide action, usually through increased capacity to quench oxygen radicals. This has been proposed as a mechanism of paraquat resistance, for example, but is only feasible if the plant also has the ability to remove the herbicide rapidly from the target site.

3.2.3 What types of herbicide resistance are being selected and why?

Every resistance mechanism present in a population should be selected by herbicide use; however, in practice, the strongest resistance mechanism tends to become dominant. The strongest mechanism will yield greater success under selection, increasing the fitness of individuals carrying it, i.e. those individuals will produce a greater number of fertile seed and contribute more to the next generation. In most broadleaf weeds, target-site resistance to the sulfonylurea herbicides is the most common because it typically provides 100-fold resistance to the herbicide.

Because of variations in the strength of resistance mechanisms between herbicides of the same MoA group, different herbicide selection can lead to different outcomes. As an example, in the 1990s, diclofop-methyl (Hoegrass®) was the main selecting agent used against wild oats. Most of the resistant populations had target-site resistance to all ‘fop’ herbicides with some resistance to the ‘dim’ herbicides. Later, when fenoxaprop-p-ethyl (Wildcat®) and clodinafop-propargyl (Topik®) became the primary herbicides used against wild oats, non-target-site resistance became
common. This conferred cross-resistance to flamprop-methyl (Judgement®), but these populations were susceptible to less selective ‘fop’ herbicides such as haloxyfop.

Patterns can also differ between weed species. Most of the resistance to Group B herbicides in annual ryegrass is target-site resistance, generally because of the strong resistance it provides to chlorsulfuron (Glean®) and triasulfuron (Logran®). In addition, at least 50% of the resistant populations have cross-resistance to imidazolinone herbicides. However, in brome grass, which has been selected mainly by iodosulfuron (Atlantis®) and pyroxsulam (Crusader®), most of the Group B resistance is low-level, non-target-site resistance with little or no cross-resistance to imidazolinone herbicides.

Other aspects of plant biology influence the development of herbicide resistance:

- Diploid v. hexaploid. Diploid species such as annual ryegrass have two copies of each gene, whereas hexaploid species such as wild oats have six copies of each gene. A single gene mutation will confer resistance in annual ryegrass; however, in wild oats, the same single mutation will have less effect because it is diluted by the presence of multiple copies of the susceptible gene. For example, for diclofop-methyl resistance, wild oat plants with a single gene mutation produce one-third resistant ACCase enzyme and two-thirds herbicide-sensitive ACCase. 36

- Self-pollinating v. obligate out-crossers. Self-pollinating species such as wild oats and brome grass are 90–100% self-fertile and so do not share many genes between plants during pollination. Ryegrass and wild radish plants must obtain pollen from another plant to fertilise the flowers, thereby readily sharing genes, including resistance genes, between plants. 37

Continued selection of the resistant populations with herbicides will result in stronger herbicide resistance, usually through the stacking or accumulation of resistance mechanisms. For example, when annual ryegrass became resistant to clethodim (Select®) at 250 mL/ha, it was found that most populations could be controlled by a rate of 500 mL/ha. Populations then became resistant to the higher rate by ‘picking up’ extra target-site mutations through obligate cross-pollination. When glyphosate-resistant annual ryegrass first occurred in vineyards, some growers increased the rates of glyphosate in an attempt to control the ryegrass. As a result, they selected for annual ryegrass with two different mechanisms of resistance, a target-site mutation and reduced herbicide translocation, which was much more resistant to glyphosate.

Weed species also become resistant to multiple MoA by accumulating herbicide-resistance mechanisms. This usually occurs through the sequential application of different MoA herbicides and the use of herbicide mixtures where the mix partners are at low label rates. Multiple resistance occurs more readily in outcrossing weed species, but can also occur in self-pollinated weed species. The worst case of multiple resistance is a ryegrass population with resistance to Groups A, B, C, L and M herbicides. This population has a combination of target-site and non-target-site resistance mechanisms. 38

### 3.2.4 Glyphosate-resistance mechanisms

Numerous mechanisms of glyphosate resistance are available to plants. Annual ryegrass tends to have reduced glyphosate translocation or target-site mutations. Brome grass is the first weed to be discovered in Australia in which resistance is due to massive gene amplification. Some barnyard grass populations contain target-site mutations but others do not, indicating multiple mechanisms of resistance in this species. One feature of glyphosate resistance in barnyard grass is that many populations become more resistant as temperature increases, due in part to lower

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uptake of glyphosate. This makes management of glyphosate-resistant barnyard grass populations more challenging. 39

Three of four species of glyphosate-resistant weeds in the northern region have non-target-site resistance mechanisms. Only feathertop Rhodes grass (which is not considered resistant) has the Pro106Ser target-site mutation. 40

### 3.3 IWM strategies

Integrated Weed Management (IWM) is the most effective way to manage weeds and thereby help to prevent or minimise the risk of resistance developing. It is the practice of using many weed-control tactics in combination within the one season to prevent the production of new weed seeds. 41

The principles of IWM are:

- Ensure that survivors do not set seed and replenish the soil seedbank.
- Keep accurate paddock records of herbicide application and levels of control. Monitor weeds closely for low levels of resistance, especially in paddocks with a history of repeated use of the same herbicide group.
- Rotate between the different herbicide groups, and/or tank mix with an effective herbicide from another MoA group. It is important to use effective 'stand-alone' rates for both herbicides in the mix.
- Aim for maximum effectiveness to keep weed numbers low. The primary aim of weed control is to minimise their impact on productivity, and resistance is much less likely to develop in paddocks with fewer weeds than in heavily infested paddocks.
- Use a wide range of cultural weed control tools in your weed-management plan. Sowing different crops and cultivars provides opportunities to use different weed-management options on key weeds. Tillage is useful when it targets a major weed flush and minimises soil inversion, because weed seed generally persists longer when buried than on the soil surface. Competitive crops will reduce seed production of weed survivors.
- Avoid the introduction or spread of weeds by contaminated seed, grain, hay or machinery. Also, manage weeds in surrounding non-crop areas to minimise risk of seed and pollen moving into adjacent paddocks. 42

Aim to include as many as possible of the risk-decreasing factors in crop and weed management plans.

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Weedsmart 10-point plan

1. ACT NOW TO STOP WEED SEEDSET:
   - Research and plan your WeedSmart strategy.
   - Understand the biology of your weeds.
   - Be strategic and committed.

2. CAPTURE WEED SEEDS AT HARVEST:
   - Consider your options—chaff cart, narrow windrow burning, baling, Harrington Seed Destructor.
   - Compare the financial cost per hectare.

3. ROTATE CROPS AND HERBICIDE MODES OF ACTION:
   - Protect the existing herbicide resource.
   - Repeated application of effective herbicides with the same MoA is the single greatest risk factor for herbicide-resistance evolution.

4. TEST FOR RESISTANCE TO ESTABLISH A CLEAR PICTURE OF PADDOCK-BY-PADDOCK FARM STATUS:
   - Resistance continues to evolve.
   - Sample weed seeds prior to harvest for resistance testing.

5. NEVER CUT THE RATE:
   - Always use the label rate.
   - Weeds resistant to multiple herbicides can result from below-the-rate sprays.

6. DO NOT AUTOMATICALLY REACH FOR GLYPHOSATE:
   - Remember—diversity, diversity, diversity.
   - Consider post-emergent herbicides where suitable.
   - Consider strategic tillage.

7. CAREFULLY MANAGE SPRAY EVENTS:
   - Use best management practice in spray application.
   - Patch-spray area of resistant weeds if appropriate.
   - Allow no escapes.

8. PLANT CLEAN SEED INTO CLEAN PADDOCKS WITH CLEAN BORDERS:
   - Plant weed-free crop seed.
   - The density, diversity and fecundity of weeds is generally greatest along paddock borders and areas such as roadsides, channel banks and fencelines.

9. USE THE DOUBLE-KNOCK TECHNIQUE:
   - Use any combination of weed control that involves two sequential strategies.
   - A second application controls survivors from the first.

10. EMPLOY CROP COMPETITIVENESS TO COMBAT WEEDS:
    - Increase your crop’s competitiveness to win the war against weeds.
    - Row spacing, seeding rate and crop orientation can all be tactics to help crops fight.

MORE INFORMATION

- AHRi: Ryegrass Integrated Management
- DAFWA: Annual ryegrass: tactics for integrated weed management
- GRDC: Integrated Weed Management Hub
- GRDC Update Papers: Herbicide resistance management, a local, in-field perspective
- GRDC Update Papers: Managing herbicide resistance
- QDAF: Effectiveness of herbicide resistance management strategies
- SANTFA: Herbicide resistance driving system change
- WeedSmart: WeedSmart app
3.3.1 Prevent weed seedset

The best way to prevent resistance developing is to stop any survivors of a herbicide application from setting seed and germinating.  

Although it is easy to combat herbicide resistance with other herbicides from a different MoA group, some non-chemical options should be implemented to reduce reliance on herbicides. The two most suitable options are adequate crop competition and strategic cultivation that minimises soil moisture losses and structural damage.  

Inversion ploughing

Inversion ploughing is used to invert the soil fully to ensure that weed seeds that were on or just below the soil surface are placed at a depth from which they cannot germinate. Inversion ploughing can be practiced every 10–15 years where no-till or reduced tillage is used in the intervening years. Inversion ploughing is particularly effective at resetting the weed seedbank and can be very useful if herbicide-resistant weeds are a problem in a no-till system. 

Inversion ploughing has been adopted in Western Australia with use of commercial, two-way machines. Mouldboard ploughs are fitted with skimmers to throw topsoil and weed seed to the bottom of the furrow. The technique is used after the break of season, immediately prior to sowing, when the soil profile is wet to a depth of at least 40 cm. Sowing immediately will reduce the chance of wind erosion. 

The process has been successful on a range of soil types, including duplex sands over clay, loamy clays and deep sands. It should be noted that for self-mulching soils, many weed seeds will already be deeply buried in soil cracks and inversion ploughing may not be an effective weed-management tactic in these soil types. 

Although whole-paddock inversion ploughing is quite expensive (estimate $70–100/ha on deep sands for an owner/operator machine, or $125/ha plus diesel for a contractor), there are long-term benefits for the reduction of the weed seedbank and the amelioration of soil problems such as water repellence in non-wetting sands and subsurface acidity. 

Autumn tickle

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

An autumn tickle can be conducted with a range of equipment 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 should be used in conjunction with delayed sowing to allow time for weeds to emerge and to be controlled prior to seeding. 

Delayed sowing

Delayed sowing allows use of knockdown herbicides or cultivation to control small weeds prior to sowing, reducing the pressure on selective herbicides.
Delayed sowing (seeding) is the technique of planting the crop beyond the optimum time for yield in order to maximise weed emergence and control prior to sowing. Weeds that emerge in response to the break in season can then be killed by using a knockdown herbicide or cultivation prior to 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 yield impact of a later sowing date. 47

Selective spray-topping

Selective spray-topping is the application of a post-emergent selective herbicide to weeds at reproductive growth stages to prevent their seedset. 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 largely targets broadleaf weeds (especially *Brassica* weed species). 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* weed species and Group A and Z resistance in wild oats (*Avena* spp.), along with the uncertain supply of the herbicide Judgement® (for wild oats), has significantly reduced the potential application of this tactic.

Wild radish seeds can be viable once an embryo is visibly formed in the pod. This can occur within 21 days of flowering. 48

Crop-topping with non-selective herbicides

Crop-topping is the application of a non-selective herbicide (e.g. glyphosate or paraquat) prior to harvest when the target weed is at flowering or early grainfill. Crop-topping aims to minimise production of viable weed seed while minimising crop yield loss.

The selectivity of the crop-topping process depends on a sufficient gap in physiological maturity between crop and weed. Crop-topping for wild radish and weed control of other brassicas in current pulse varieties is not recommended because of the closely matched rate of development of weed and crop.

Non-selective herbicide crop-topping registrations are largely limited to use in pulse crops and predominantly target annual ryegrass. Crop-topping can reduce annual grass weed seedset, reducing additions to the seedbank.

Reducions in seedset achieved by crop-topping can be increased if it is used in conjunction with selective herbicide treatments such as pre-emergent herbicides.

Crop-topping can deliver a number of benefits in addition to reducing weed seedset, 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.

The ideal time for crop-topping is when the annual ryegrass is just past flowering and the pulse crop is as mature as possible. However, some crop yield loss will usually occur. Product labels should be consulted for specific directions. Crop-topping should not be performed on crops if the grain is intended for use as seed or for sprouting because the herbicide can affect seedling vigour and viability. 49

Weed wiping

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

Weed wiping is selective because of the application method rather than the herbicide used.

Weeds must be at least 30 cm taller than the crop. Care is needed to ensure that excess herbicide does not drip onto the crop and cause damage.

The best time to use weed wiping is when the target weed is most vulnerable. For Brassica weed species, wiping at flowering to early podfill stages will achieve the greatest reduction in seedset. The level of weed control decreases after the weed reaches mid podfill.

Weed-wipers have developed considerably since the single-rope, gravity-fed models of the late 1970s. There are models with multiple ropes, carpets, sponges, revolving cylinders and pressurised supply, making them significantly more effective. 50

Crop desiccation and windrowing

Crop desiccation with a non-selective herbicide and windrowing (also called swathing) are harvest aids that are independent of the growth stage of any weeds present. However, if conducted when weeds are green and growing, windrowing and crop desiccation can significantly reduce weed seedset.

These practices are conducted at or just after crop physiological maturity. The greatest levels of weed control will occur if the crop matures before the weeds, so short-season cultivars are best suited.

Windrowing and desiccation can:
- 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).

Any weed regrowth must be controlled to minimise seed production.

Harvest-withholding periods must be known before using herbicides for crop desiccation. 51

Pasture spray-topping

Pasture spray-topping involves application of a non-selective herbicide at flowering of the weeds, followed by heavy grazing, to reduce weed seedset.

Pasture spray-topping is possible because annual grasses become more sensitive to non-selective knockdown herbicides during flowering. This increased sensitivity allows lower rates of herbicide to be used to prevent the formation of viable grass seeds, with limited effect on desirable pasture species.

Normally, it is possible to target only one species with pasture spray-topping because of differences in time of flowering between species. Seed production of annual ryegrass can be reduced by up to 90% and barley grass (Hordeum spp.) by approximately 65%, owing to its extended head emergence.

Pasture spray-topping should be used for two years before growing a cereal crop, in order to reduce grass numbers. It is not a substitute for long fallow.

Although pasture spray-topping is targeting a different plant growth stage (i.e. flowering and seedset), a plant already resistant to that herbicide MoA will exhibit little or no effect. 52

**Manuring, mulching and hay freezing**

Sacrifice of a portion of the crop as a way to manage weed patches that have escaped control can be a particularly effective management tool.

Crops and pastures can be returned to the soil by burying, mulching or chemical desiccation with the key aims of reducing weed seedbanks, improving soil fertility and maintaining soil organic matter.

Green manuring incorporates green plant residue into the soil with a cultivation implement, whereas brown manuring uses non-selective herbicides to kill the crop prior to incorporation.

Mulching is similar to brown manuring but involves mowing or slashing the crop or pasture and leaving the residue laying on the soil surface.

Hay freezing is similar to brown manuring with the additional aim of creating standing hay. In this case, herbicide is applied earlier than if the crop were to be mown for conventional haymaking.

If performed before weed seedset and all weed regrowth is controlled, reductions in weed seedset of >95% are possible. 53

**Grazing of crop residues**

Grazing of 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. Grazing can be used to dispose of, and gain value from, fodder contaminated by weed seed.

However, grazing livestock can distribute weed seeds across a paddock. Grazing is successful in reducing weed-seed numbers only in weeds that are palatable and where the seeds can be easily eaten and digested. 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. 54

**Encouraging insect predation of seed**

The contribution that insects make to seedbank reduction is often overlooked, despite weed seeds being a major component of many insect diets. This predation of seed contributes to ‘natural mortality’ and partly explains why less seed germinates than is produced.

Understanding the role that insects play in removing weed seeds could help the development of farming systems that encourage greater removal of seeds from the soil.

seedbank. In New South Wales, seed theft by ants has commonly caused failure of pastures, and data from Western Australia show that ants can remove 60% or more of annual ryegrass in no-till systems, where weed seed is on the soil surface and accessible. Therefore, weed seedbanks could also be decreased by encouraging ant predation.  

### 3.3.2 Harvest control of weed seed

A key strategy for reducing the impact of resistant weeds is the collection and/or destruction of weed seeds at harvest. A major premise of this approach is that the targeted weed species retain a high proportion of their total seed production at crop maturity and that this seed is subsequently collected during harvest. Research by AHRI found that 70–98% of weed seeds remain on various weed species at harvest (Figure 1). In the past, these retained weed seeds were harvested and then spread back across the paddock with the chaff fraction, but methods of capturing and removing both resistant and susceptible weeds that have survived earlier herbicide applications are increasingly being adopted to slow herbicide resistance evolution and reduce pressure on subsequent herbicide use.

![Figure 1: Seed retention rates for four weed species in AHRI trials in WA in 2008. Each retained at least 75% of their seeds above ‘beer-can’ cutting height at the first opportunity to harvest.](source)

Because annual grass seed does not remain viable in the soil for very long and seedbanks decline rapidly if not replenished with annual seed production, methods of control of harvest weed seed can reduce a very large seedbank of >1000 seeds per m² to 100 seeds per m² in only four years.

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AHRI research has compared the effectiveness of four harvest methods of control of weed seed: chaff carts, baling, narrow-windrow burning, and the Harrington Seed Destructor. Carried out over 25 sites across four states and over two harvests, the research found that the systems were equally effective at removing ryegrass seed from cropping systems. Averaged across the 25 sites, each of the methods removed approximately 55% of annual ryegrass seed. The system chosen will therefore depend on personal preference, and on best fit within a particular farming system.

Research by the Department of Agriculture and Food WA (DAFWA) has shown harvest systems for control of weed seed to be highly effective at removing the final few weeds in cropping paddocks when combined with a pre-emergent herbicide. The research has monitored the impact of pre-emergent herbicides with and without narrow-windrow burning and chaff carts on annual ryegrass populations of 31 cropping paddocks in the north of Western Australia over 13 years. Despite starting with a larger seedbank, growers who implemented regular harvest control of weed seed in the form of narrow-windrow burning or chaff carts eroded their annual ryegrass population to very low levels in four years. By the eighth year, these growers had fully depleted annual ryegrass from their focus paddocks, and since then have averaged fewer than 1.5 ryegrass plants per m². Although the growers using only herbicide have also been very successful at eroding the ryegrass seedbank, such a heavy reliance on herbicides is likely to result in higher levels of herbicide resistance in these paddocks, making the few remaining plants expensive to contain.  

Five tools are commercially available to remove weed seeds at harvest: chaff carts, windrow burning, Harrington Seed Destructor, baling direct, diverting chaff to tramlines. A sixth tool, windrow rotting, is in development. All of these tools target the chaff fraction bearing the weed seed and can potentially control approximately 95% of weed seeds that enter the front of the harvester (Table 21).  

Table 21: Harvest-control options for weed seed.

<table>
<thead>
<tr>
<th></th>
<th>Windrow burn</th>
<th>Chaff cart</th>
<th>HSD</th>
<th>Bale direct</th>
<th>Divert chaff to tramlines</th>
<th>Windrow burning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry cost</td>
<td>$0 to $500</td>
<td>$30k to $75K</td>
<td>$200K</td>
<td>$100k to $150K</td>
<td>$1K to $15K</td>
<td>$0 to $200</td>
</tr>
<tr>
<td>Nutrient cost</td>
<td>High</td>
<td>Moderate</td>
<td>Nil</td>
<td>High</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>High yielding crops</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Controlled traffic farming require</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Best suited to</td>
<td>Low rainfall canola/pulses</td>
<td>Everywhere – good with sheep</td>
<td>High production</td>
<td>Market for bales</td>
<td>Controlled traffic farming</td>
<td>Controlled traffic farming + direct seeder</td>
</tr>
<tr>
<td>Negatives</td>
<td>Nutrient removal burning</td>
<td>Burning</td>
<td>Cost maintenance</td>
<td>Nutrient removal Market access</td>
<td>Weeds still in paddock CTF only</td>
<td>Weeds still in paddock CTF only</td>
</tr>
<tr>
<td>Positives</td>
<td>Low cost of entry</td>
<td>Cost effective Whole farm Sheep feed</td>
<td>Residue retention Whole farm</td>
<td>More profit if market for bales</td>
<td>Cheap Easy Whole farm</td>
<td>Cheapest Easy Whole farm</td>
</tr>
</tbody>
</table>

Source: AHRI 61

Chaff carts

Chaff carts are towed behind headers during harvest to collect the chaff fraction. Collected piles of chaff are then burnt during the following autumn or used as a source of stock feed. Because of the considerable volume of chaff material produced during harvest, chaff heaps are typically burned. 63

There has been a significant resurgence in the use of chaff carts in Western Australia, with the addition of a conveyor belt to deliver the chaff fraction from the harvester to the cart, making the system more user-friendly. The conveyor belt adaptation creates chaff dumps that burn out in a shorter period, thus reducing the risk of fire escapes. 64

The weed-seed collection efficiency of several commercially operating harvesters with attached chaff carts was evaluated by AHRI. Harvesters were found to collect 75–85% of annual ryegrass seeds and 85–95% of wild radish seeds entering the front of the header during the harvest operation. Collected chaff must be managed to remove weed seeds from the cropping system. 65

Narrow-windrow burning

A widely adopted alternative to chaff carts, the harvested straw and chaff fraction are funneled into narrow windrows for subsequent burning in autumn. This system requires only a simple modification to the harvester and is cheap and easy to use. According to AHRI and DAFWA, burning narrow windrows consistently destroys more weed seed than burning standing stubble. This is due to the higher temperature burn achieved in the narrow rows. Concentrating the stubble into a narrow windrow and burning in a light wind increases the intensity of the burn and allows higher temperatures to be reached for longer, which is crucial for destroying weed seeds, especially wild radish. The researchers also calculated that less than 10% of a paddock is exposed to erosion when burning narrow windrows rather than the entire paddock. 66

Narrow-windrow burning is a simple, low-cost way of destroying weed seeds and can significantly reduce weed seedbanks.

AHRI research, supported by the Grains Research and Development Corporation (GRDC), shows that 99% of annual ryegrass and wild radish seeds entering the harvester are destroyed in narrow-windrow burning systems. Often, however, only 70–80% of weed seeds enter the front of the harvester, meaning 70–80% efficacy of destruction of the total set weed seed.

AHRI research shows that narrow-windrow burning is just as effective for other annual weed species, including brome grass and wild oats, and works in windrows of cereal, canola and lupin stubble.

When conditions are right and weed infestations at harvest are moderate (approximately five plants per m²), weed numbers will likely drop significantly in the first year. If weed numbers are high at harvest (approximately 10–50 plants per m²), it may take several years to see a reduction in populations.

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**Tips for harvesting**

The narrow-windrow burning system requires only simple modifications to the harvesting process and is cheap and easy to use. To optimise the number of weed seeds entering the front of the harvester, crops should be cut as low as possible (e.g. ‘beer-can’ height or lower).

By using a mounted chute at the back of the harvester, straw and chaff fractions are funneled into narrow windrows 500–600 mm wide. Many growers in the northern wheatbelt of Western Australia use a chute that is the width of the shaker tray and has a minimum gap at the base of approximately 500 mm for trash to flow out, which is especially important in canola crops. Some growers in southern areas have set up a system of reverse spinners on the harvester. These direct chaff to adjacent, heavy-duty PVC tubes and deposit it on top of the straw windrow.

Regardless of the modifications used to make narrow windrows, these systems potentially block when the harvester stops. When there is a stop, it is therefore recommended that the machine be shut down and then reversed up before starting again. There is still material coming out of the harvester, and this action will avoid it piling up in the chute and then blocking up the header.

**Where to place the chaff in the windrow**

Some growers claim that placing the chaff and weed-seed fraction on top of the straw windrow destroys more weed seeds, because they are in the hottest part of the fire when windrows are burned in autumn. However, AHRI research has shown that regardless of where chaff is placed on the windrow, the weed seeds have generally settled on the soil surface by the time the burning season starts the following autumn.

**Tips for achieving a burn that kills weed seeds**

The longer the duration of high temperatures at the soil surface, the more weed seeds are destroyed. AHRI has found that the ideal soil-surface temperature for annual ryegrass seed kill is 400°C or hotter for at least 10 seconds. This same temperature maintained for 30 seconds will ensure the destruction of wild radish seeds, or the same result can be achieved for wild radish from a hotter fire of at least 500°C for 10 seconds.

Pulse and canola stubbles burn well and safely, and AHRI researchers say these are the best to trial when starting a narrow-windrow burning system. Burning narrow windrows in high-yielding wheat and barley crops (i.e. yields >3 t/ha) is risky because of high residue levels and should be avoided if possible.

The efficacy and safety of windrow burning depends on environmental conditions. High temperatures, unsuitable wind conditions and rainfall can restrict burning efficacy. AHRI recommends using a fire weather index that takes into account temperature, humidity and wind speed to rate burning conditions.

Higher temperatures increase the risks of fire escapes, especially when burning larger cereal crop windrows.

Rainfall reduces burning temperatures, and if the windrow is wet, it will not burn right to the soil surface. In this situation, it is recommended to wait for about two weeks, or at least until all but the bottom few centimetres of the windrow is dry.

The most important factor is wind. A light breeze of approximately 5–10 km per hour is best to fan the fire.

A light crosswind at right angles to the windrows supplies oxygen for the fire and ensures that it burns slowly right through the windrow.  

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Baling direct

An alternative to the in-situ burning or grazing of chaff is to bale all chaff and straw material as it exits the harvester. Initially developed as a way to improve straw hay production, the Glenvar Bale Direct System® developed by Graham Shields, a grower from Wongan Hills, Western Australia, consists of a large square baler directly attached to the harvester that collects and bales all harvest residues. AHRI research shows that 95% of annual ryegrass seed entering the harvester was collected in the bales. In addition to removing weeds, the bales can be sold or used as a feed source. However, as with all baling systems, the cost of removing nutrients from the cropping system needs to be considered. 68

Harrington Seed Destructor®

Developed by Western Australian grower and inventor Ray Harrington, the Harrington Seed Destructor is a trail-behind unit consisting of a chaff-processing cage mill, and chaff and straw delivery systems. It has its own power supply.

The Harrington Seed Destructor is a unique weed-seed control system, smashing the chaff and weed-seed fraction as it exits the harvester, destroying seed viability and returning the crushed fraction to the paddock. Unlike other systems harvesting weed seed, there is no need for autumn burning and chaff and nutrients remain in the paddock. AHRI research has shown that the Harrington Seed Destructor consistently destroys 95% of annual ryegrass, wild radish, wild oats and brome grass seed present in the chaff fraction. 69 70

Engineers at the University of South Australia have modified the original design and developed a machine that is hydraulically driven and mounted to the rear of the harvester. 71 The de Bruin Group in South Australia has exclusive rights to the manufacture of the new machine, and machinery dealers McIntosh and Son will distribute the machines nationally.

Known as the integrated Harrington Seed Destructor (iHSD)®, the new machine comprises two hydraulically driven cage mills mounted within the rear of the harvester just below the sieves.

Several Case harvesters around Australia are fitted and working with iHSDs. Ten more harvesters (Case and New Holland) will have been fitted with iHSDs by harvest 2016, all in Western Australia. These were already allocated to customers and will be closely monitored and fine-tuned. The iHSD will be fitted to other makes of harvester in 2017. 72

Diverting chaff to tramlines

This system has taken off in Western Australia with the development of the ‘chaff deck’, which was invented by a grain grower in Western Australia and then commercially produced by James Buttle in Esperance. Forty of these units are in operation in the Esperance area and another 30 or so will have been produced for harvest 2016. Owing to this high demand, Primary Sales Australia have been contracted to build some chaff decks. The chaff deck simply places the chaff from the sieves of the harvester onto permanent wheel tracks and is applicable for growers with fully matched tramline farming systems. Some growers with these systems have disc-seeding modules
to seed the tramlines because a tyne disrupts the chaff fraction and is at risk of blockages.

Growers using this system have observed that weeds seldom germinate from this chaff fraction, and they believe that many weed seeds rot in the chaff. Presently, only anecdotal reports exist of the efficacy of this system, and there are plans to evaluate this system in the near future. 73

Windrow rotting

Windrow rotting was developed by Esperance grower, Mic Fels. This technique involves diverting just the chaff fraction into a narrow windrow in the middle of the harvester rather than on the permanent wheel track, by using a plastic chute to concentrate the chaff fraction and spreading the straw. This narrow chaff windrow is then left to rot. Very few weeds germinate in this chaff windrow and many seem to rot, hence the name. Again, there are only anecdotal reports of efficacy at this stage, and future research will evaluate this system. Windrow rotting appears to be ideal for controlled-traffic farming systems and is most compatible with disc seeding so that blockages do not occur and the chaff row is not disturbed. 74

3.3.3 Double-knock

One of the most successful tactics to minimise ‘escape’ weeds and counter the buildup of resistance is the double-knock spraying strategy. Double-knock refers to the sequential application of two weed-control tactics applied in such a way that the second tactic controls any survivors of the first tactic. A common combination is glyphosate followed by paraquat or paraquat/diquat.

Benefits:

- Double-knock delays or prevents the development of glyphosate resistance.
- Use of a double-knock strategy reduces the number of (potentially resistant) weeds to be controlled in crop.
- Excellent control of weed seedlings is achieved.

Considerations:

- Glyphosate should be applied first, followed by paraquat or paraquat/diquat.
- The timing between applications will vary depending on the main target weed species (see example in Table 22).
- Consider the main target weed species when choosing which herbicides to use in the double-knockdown.
- Double-knock is more expensive than a single herbicide application.
- Seasonal conditions will influence the scale of on-farm implementation because a double-knock takes more time than a single application. 75

The key to implementing the double-knock strategy is to understand that it is a two-phase tactic targeting weeds of the same generation. Therefore, the tactic can be used several times during a fallow period, targeting different generations of weeds. 76

It is imperative that lethal rates of herbicide be used for both knocks. The aim of the double knock is to ensure that no resistant weeds survive. Cutting the rate of either of the ‘knocks’ will jeopardise this. 77

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**Best application timing**

To obtain maximum performance when using two different herbicides as a double-knock, apply the second herbicide before the full effect of the first application is evident. Poor results are regularly seen where the second knock is applied as an afterthought, or when the application has been delayed until the first knock is showing signs of recovery. Poor control with the second knock is often due to the weeds becoming too large or too stressed or having insufficient photosynthetic material to allow bipyridyl herbicides to work effectively.\(^78\)

Table 22: Suggested intervals for some common double knock herbicide combinations in the northern grains region.

<table>
<thead>
<tr>
<th>Weed</th>
<th>First application</th>
<th>Second application</th>
<th>Recommended timing Details</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Broadleaf weeds</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Most broadleaf weeds</td>
<td>Glyphosate</td>
<td>Group L (e.g. paraquat)</td>
<td>7–21 days. Optimal</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>timing generally 10–14</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>days</td>
<td></td>
</tr>
<tr>
<td>Difficult-to-control weeds</td>
<td>Group I (e.g. Amicide(^6) Advance, Tordon(^8)) with or without glyphosate</td>
<td>Group L (e.g. paraquat)</td>
<td>7–21 days. Optimal</td>
<td></td>
</tr>
<tr>
<td>such as fleabane (Conyza bonariensis)</td>
<td></td>
<td></td>
<td>timing generally 7–10</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>days</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Glyphosate plus</td>
<td>Group L (e.g. paraquat)</td>
<td>7 to 21 days. Optimal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>saflufenacil</td>
<td></td>
<td>timing generally 10–14</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>days</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>If interval is &gt;14 days, use maximum label rates of Group L herbicide</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Only target rosettes &lt;6-leaf</td>
<td></td>
</tr>
<tr>
<td>Difficult-to-control weeds</td>
<td>Glyphosate</td>
<td>2, 4-D</td>
<td>2–4 days</td>
<td></td>
</tr>
<tr>
<td>such as sowthistle–milkthistle</td>
<td></td>
<td></td>
<td>Recommended to split applications due to incompatibility within the plant. Both products are systemic, so the interval needs to be short</td>
<td></td>
</tr>
<tr>
<td>(Sonchus oleraceus)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Glyphosate</td>
<td>Group L (e.g. paraquat)</td>
<td>7–10 days</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Only target small rosettes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Glyphosate plus</td>
<td>Group L (e.g. paraquat)</td>
<td>7–21 days. Optimal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>saflufenacil</td>
<td></td>
<td>timing generally 10–14</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>days</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Only target small rosettes</td>
<td></td>
</tr>
<tr>
<td><strong>Grass weeds</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Most grass weeds including: annual ryegrass (Lolium rigidum), barnyard grass (Echinochloa colona, E. crus-galli)</td>
<td>Glyphosate</td>
<td>Group L (e.g. paraquat)</td>
<td>4–14 days. Optimal</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>timing generally 5–7</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>days</td>
<td></td>
</tr>
<tr>
<td>Feathertop Rhodes grass (Chloris virgata)</td>
<td>Haloxyfop (PER 12941, Qld only)</td>
<td>Group L (e.g. paraquat)</td>
<td>7–14 days. Optimal</td>
<td>Refer to APVMA permit 12941</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>timing generally 7–10</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>days</td>
<td></td>
</tr>
</tbody>
</table>

Source: GRDC\(^79\)

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3.4 Managing specific resistant weeds

3.4.1 Annual ryegrass

Clethodim is the last Group A herbicide that provides effective control of herbicide-resistant annual ryegrass. It has become an exceptionally important herbicide in annual ryegrass weed-management strategies. The loss of clethodim to resistance will make annual ryegrass management more difficult. 80

In the absence of effective post-emergent herbicides, annual ryegrass management must rely on pre-emergent herbicides and non-chemical tactics. To optimise use of pre-emergent herbicides, it is important to understand some of their characteristics and how they will perform under different conditions.

Trifluralin and Stomp® (pendimethalin) have low water solubility so tend to stay where they are applied. Therefore, they need to be placed in close proximity to the weed seed. These herbicides are also volatile, so need to be incorporated shortly after they are applied to avoid losses. They bind tightly to organic matter, including stubble. If there is too much stubble, some will need to be removed to allow these herbicides to work effectively.

Boxer Gold® (prosulfocarb + S-metolachlor) has high water solubility and it will move readily through the soil. Typically, 5–10 mm of rainfall is required over a week to activate the herbicide. If heavy rainfall occurs after application, some crop damage may occur. Wheat is more sensitive than barley, so damage will be greater in wheat crops. The product has medium binding to organic matter, so will move more readily in soils of low organic matter. If heavy rainfall occurs after application, some crop damage may occur. Prosulfocarb + S-metolachlor has relatively short persistence, so late-emerging weeds will be a problem in high-rainfall zones.

Sakura® (pyroxasulfone) has lower water solubility, making it less likely to move in soil. It requires more rainfall than prosulfocarb + S-metolachlor to activate at 10–15 mm. Pyroxasulfone is not bound tightly to soil, but its low water solubility means that it is normally not highly mobile. However, in soils with low organic matter or after large rainfall events some crop damage may occur. Pyroxasulfone is active for an extended period.

Avadex® Xtra (triallate) on its own will control annual ryegrass at high concentrations only. It is volatile and requires incorporation. It is more mobile in soil than trifluralin and binds less tightly to organic matter. It is primarily absorbed through the coleoptile rather than the roots, so controls deeper emerging weeds (Note: Avadex® Xtra is not registered to control ryegrass on its own, only when mixed with TriflurX®, Lusta® or Nugran®)

Rustler® (propyzamide) is similar to Sakura® (pyroxasulfone) in its behaviour. It has low water solubility and medium binding to organic matter in the soil. This means that it usually does not move far through the profile, but can do so with heavy rain. Propyzamide is registered for control of annual ryegrass (and other weeds) in canola. Canola tends to be sown shallower than wheat, so the herbicide is closer to the crop. Therefore, propyzamide damage to canola is more likely with high rainfall. 81

3.4.2 Sowthistle

The increase in glyphosate resistance in sowthistle means that alternative chemical and non-chemical options are required for its management. By including different management tactics such as the double-knock and strategic tillage, the risk of resistance to glyphosate and other MoA will be reduced, and management of populations that are already resistant will improve.


In a QDAF field trial in 2013 near Cecil Plains on Queensland’s Darling Downs, double-knock treatments were the most effective fallow treatments and were equally effective on small sowthistle plants (<10 cm diameter, 97–100% control) and larger plants (>10 cm diameter to elongating, 95–100% control). Most double-knock treatments provided 100% control, thereby preventing any production of weed seed.

None of the single-knock treatments were as effective as the double-knock treatments, even at higher rates. Increasing the rate of herbicides did improve the control of small plants for Spray.Seed® (paraquat + diquat), Tordon™ 75-D (2,4-D + picloram) + Roundup® (glyphosate), Starane™ Advanced (fluroxypyr) + Roundup® (glyphosate), and Alliance® (amitrole + paraquat). However, even at the higher rates, these treatments provided only 88–97% control, thereby allowing survivors to grow and set seed.

The impact of different forms of tillage on seed burial and subsequent emergence has been investigated in four field and two pot experiments. In all field experiments, harrows resulted in the least seed burial (majority at 0–2 cm) and one-way discs the most seed burial (majority of seed buried below 5 cm). Glasshouse pot experiments have shown that emergence of sowthistle is greatest when seed is sown on the soil surface, and is reduced when sown at 2 cm. For sowthistle, offset discs and one-way discs reduced emergence compared with no-tillage in all field trials, but in two field trials, harrows and chisel ploughs increased seedling emergence. The timing and amount of rainfall during the trial can partly explain these differences.

NSW DPI pot experiments in 2014 compared effects of systemic herbicide and paraquat tank mixtures applied under sunlight or evening conditions on glyphosate-resistant sowthistle and found that the sowthistle was fully controlled by the tank mixes at the early flowering growth stage. There was no difference in control between day and night applications of these tank mixes. Although glyphosate-resistant, the sowthistle was controlled with a treatment containing glyphosate + paraquat when applied during the day or during the evening. A tank mix of paraquat and Velocity® (bromoxynil + pyrasulfotole) appears to have good potential owing to its excellent early brownout of sowthistle, irrespective of day or evening application. The brownout (speed of plant death) was faster than the other treatments examined in this study.

NSW DPI pot experiments in 2014 also compared effects of night-spraying tank mixes and double-knock on glyphosate-resistant sowthistle, using boom-spray rates. The sowthistle was completely controlled by night tank mixes and by standard double-knock of selected systemic herbicides and paraquat at the early flowering growth stage. There was no benefit of applying paraquat after sunset (night spraying) for better brownout of sowthistle. This is contrary to research findings for weeds such as awnless barnyard grass. Some incompatibility problems arose with paraquat and 2,4-D amine products, a phenomenon seen in another experiment on fleabane. A tank mix of paraquat and Balance® (isoxaflutole) appears to have good potential with its excellent early brownout of sowthistle, which was faster than the other treatments examined in the study.

In April 2015, it was confirmed that sowthistle in South Australia had resistance to 2,4-D, a Group I herbicide. The University of Adelaide found that mixtures with 2,4-D and other Group I herbicides were still likely to be effective in controlling these populations provided there was a robust rate of the mixing partner and the herbicide was applied to small seedlings. Otherwise, alternative herbicides will have to be used to control the resistant populations. Apart from Group B and Group I herbicides, few

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herbicides can be used to control established sowthistle in crops, so attacking it early is the key. 85

3.4.3 Wild radish

Field experiments conducted by the NSW DPI after the detection of Group I-resistant wild radish in 2013 at Nyngan showed that several alternative herbicides could maintain excellent control. These herbicides are generally suited to application in winter cereal crops but some others can be applied in broadleaf winter crops. Managing herbicide-resistant wild radish by simply rotating herbicide MoA works well, but if doing this for prolonged periods, herbicide resistance to other groups is likely. To combat this, harvest weed-seed management tactics such as windrow burning to extend herbicide effectiveness are strongly recommended. 86

The key to long-term management is to drive the wild radish seedbank down to very low levels. Extended seedbank persistence requires a concerted effort over many years.

Crop competition can be a valuable tool for reducing weed numbers. Where possible, strive for high sowing rates and narrow row spacing to maximise crop competition. Wheat and barley compete more aggressively than broadleaf crops and generally have a wider range of available herbicide options. Barley has some added benefits in that it provides even greater crop competition than wheat, and with a generally shorter growing season, sowing can be delayed to allow a germination and subsequent knockdown treatment prior to sowing.

If a spray failure occurs, radical and drastic action should be considered to prevent more seed from replenishing the seedbank, which would then need to be controlled for a further six years or more. Thoroughly check all crops prior to commencement of flowering, and if wild radish plants are detected, consider sacrificing that part of the crop via a spray-out (brown manuring), cultivation, slashing, cutting for hay or silage, or hand rogueing. Wild radish seeds become viable within three weeks from the appearance of first flowers, so it is important to kill those plants before this stage.

Some herbicides are registered for late-season application as a salvage spray (always observe withholding periods). If the population is susceptible to that MoA, this can be a useful management tool for reducing the amount of viable seed that may return to the soil. However, these late-season applications rarely provide 100% weed kill or seed sterilisation, so are better used as an integrated tactic to drive down numbers of weed seed further rather than a method relied on to ‘fix blowouts’.

Harvest control of weed seed has proven to be an excellent non-chemical tactic to reduce wild radish numbers when applied to a paddock over multiple years, especially when used in conjunction with effective herbicides.

Herbicide control remains a key tool for managing wild radish populations; however, the choice of herbicide is increasingly dictated by resistance to multiple MoA. Typically, most herbicide strategies in high-pressure situations will contain a mixture of two or three MoA and two application timings.

One of the keys to effective herbicide control is to target small weeds. The timing of the first post-emergent application in cereals should be when weeds are a rosette <5 cm in diameter (the size of the top of a beer can). Ensure that coverage is thorough, including using high water rates, slow application speeds and correct nozzle selection. Triazine-tolerant (TT), Clearfield® and Roundup® Ready canola varieties may also be useful tools because they allow the use of different herbicides in the canola phase of the rotation when populations are sensitive to these herbicides.

Some growers have resorted to full-inversion tillage as a wild radish control option, with the aim of burying the seed to a depth of more than 20 cm, preventing germination. However, deep burial of wild radish seed will increase the length of time required for germination to occur, thereby reducing the effectiveness of this control tactic.

that this seed remains viable in the soil, so further cultivation should be avoided for at least 10 years. 87

In the Northern Agricultural Region of Western Australia, the widespread use for many years of effective and low-cost herbicide mixes in cereals, based mainly on Group I and B chemistry, has led to an alarming level of resistance in wild radish. The more expensive broadleaf herbicides have also been used at below the label rates for many years. Coupled with often-poor application conditions and water volumes, this has created significantly enhanced selection pressure. In many cases, these wild radish populations have also had significant exposure to Group F and C herbicides in both cereal and broadleaf crops. Plants surviving these herbicide groups over many seasons have shared resistance genetics and have created resistance to multiple herbicide groups within wild radish populations and individual plants, resistant to several MoA.

Also of significant concern to the industry is the repetitive use of two new herbicides (Precept® and Velocity®) that contain the relatively new active pyrasulfotole (Group H). In many cases, cereal crops are receiving two applications of pyrasulfotole to achieve acceptable wild radish control. Given the overuse and abuse of older MoA, the industry as a whole needs to be very conscious of using this new active carefully, in order to prolong its life within these farming systems.

In 2012, work conducted by Planfarm and AHRI in the Northern Agricultural Region of Western Australia showed that many two-spray strategies were successful in controlling wild radish with resistance to multiple herbicide groups through timely application and good water volumes with robust herbicide rates. The second year of work (2013), conducted at different locations on different populations in the region, also demonstrated that the best practice management of multiple herbicide group resistance in wild radish involves early spraying followed by a quick and timely second spray with robust herbicide rates.

The 2013 data clearly showed that there are options for the two-spray strategy other than the two consecutive doses of pyrasulfotole (Group H). However, the data also showed that herbicide mixes containing pyrasulfotole are highly effective and reliable in many conditions. The study demonstrated significant improvements in efficacy and grain yield by implementing a two-spray strategy when wild radish density is high.

The focus of the Regional Cropping Solution Network group in the Northern Agricultural Region was to develop alternative control options to prevent the overuse and abuse of the Group H active pyrasulfotole. Trial data provided several reliable alternatives to the two Group H products; however, in identifying those options, a new problem emerged. Many of the non-Group H options identified contained bromoxynil, and in attempts to preserve and use Group H wisely, it is also important to guard against inadvertent abuse and overuse Group C chemistry, specifically bromoxynil.

Addition of Ecopar® (pyraflufen-ethyl, Group G) to Tigrex® and to Precept® achieved consistently high levels of control of wild radish. Although these treatments caused high levels of crop phytotoxicity early, crops had recovered by 32 days after application. However, the top two wheat leaves at the time of application had completely senesced. Whereas there was no significant yield loss in this dry season, yield losses could occur in a better season where more crop biomass leads to higher grain yields. If growers and advisers are willing to accept this crop effect, then these treatments could also become a very useful alternative.

The data from one site also raise some questions. Resistance testing identified a poor level of activity from Groups B, F and I, yet one treatment (Estercide® + Logran®, Groups I and B) eventually achieved 100% control of wild radish when used as a stand-alone or after an early spray. This treatment took a very long time to achieve a complete kill of wild radish; however, it does cast doubt over the value of herbicide-resistance testing as a sole determinant of a population’s resistance status in a whole

paddock. Actual in-paddock herbicide MoA and rate-response screens are a much more reliable method of determining a resistance status of a population. 88

### 3.4.4 Brome grass

The incidence of herbicide resistance in brome grass is increasing in southern Australia. Resistance to Group A herbicides was first reported in north-western Victoria in 2006, and now is also present in several areas of South Australia.

Resistance to Group B herbicides in brome grass was subsequently reported in South Australia and Victoria. 89

As brome grass resistance to post-emergent herbicides increases, growers will be increasingly reliant on pre-emergent herbicides as their main control for this weed in cereals. Trials were conducted over three years (2012–14) in the South Australian Mallee to identify the best options for brome grass control with pre-emergent herbicides. Brome grass is difficult to control with pre-emergent herbicides because it tends to have delayed emergence, which requires the use of herbicides with longer residual activity.

The trials established that a trifluralin + metribuzin mixture reduces brome seed production by only approximately 50% and as such is insufficient to keep brome grass populations in check. None of the other herbicide mixtures used were very effective. The most effective of the herbicide treatments examined, Sakura® (pyroxasulfone) + Avadex® (triallate), provided good brome grass control (>70%) in most of the field trials. However, where moisture conditions were inadequate and brome grass had already germinated but not emerged, this mixture struggled to provide adequate control. Pre-emergent herbicides are susceptible to low moisture conditions after application and such conditions are likely to occur more often in low-rainfall environments.

Sakura® + Avadex® is an expensive mixture and is unlikely to be cost-effective for general use in the Mallee. Therefore, other strategies will have to be adopted. A period of two years of excellent control is essential for driving down brome grass seedbanks. Intensive management of brome grass in the break crop or pasture phase, including seedset control, will become essential to brome management in cereals. 90

### 3.4.5 Wild oats

Resistance in wild oats to one MoA herbicide is very common in most parts of the northern grain region, specifically for post-emergent herbicides. Farmers overcome this problem by selecting another post-emergent herbicide from a different MoA. However, the steady increase in multiple-resistant wild oats has forced farmers to make substantial changes.

There are many examples of multiple resistance or cross-resistance. In some cases, there can be resistance to three herbicide groups (Groups A, B and Z). However, in extremely serious cases of multiple resistance, a few post-emergent herbicides are still likely to work. A population of wild oats from Edgeroi, north-western New South Wales, was confirmed resistant to Group A, B and Z herbicides but was still susceptible to Verdict® (haloxyfop) and high rates of Select® (clethodim).

The mechanisms controlling resistance within wild oat plants are complex, and a resistance test is the best way to determine which herbicides are still likely to work and which are not.

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Growers with wild oats that have resistance to one or two herbicides groups (Group A, B or Z, Groups A and B, Groups A and Z) could use a pre-emergent herbicide followed by the remaining useful post-emergent option. The data in Table 23 illustrate this strategy.

Table 23: Controlling Group A-resistant wild oats, North Star.

<table>
<thead>
<tr>
<th>Herbicide</th>
<th>Rate of product per ha</th>
<th>Herbicide MoA group(s)</th>
<th>No. of wild oat seeds per m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>–</td>
<td>–</td>
<td>90.7</td>
</tr>
<tr>
<td>Achieve® (post-em.)</td>
<td>380 g</td>
<td>A</td>
<td>43.8</td>
</tr>
<tr>
<td>Topik® (post-em.)</td>
<td>65 mL</td>
<td>A</td>
<td>180.9</td>
</tr>
<tr>
<td>Wildcat® (post-em.)</td>
<td>300 mL</td>
<td>A</td>
<td>123.3</td>
</tr>
<tr>
<td>Avadex® Xtra (pre-em.)</td>
<td>1.6 L</td>
<td>J</td>
<td>9.4</td>
</tr>
<tr>
<td>Trifluralin® 480 (pre-em.)</td>
<td>1.5 L</td>
<td>D</td>
<td>47.8</td>
</tr>
<tr>
<td>Judgement® 90 (SST)</td>
<td>1.875 L</td>
<td>Z</td>
<td>0.4</td>
</tr>
<tr>
<td>Hussar® (post-em.)</td>
<td>200 g</td>
<td>B</td>
<td>2.3</td>
</tr>
<tr>
<td>Atlantis® (post-em.)</td>
<td>330 mL</td>
<td>B</td>
<td>4.2</td>
</tr>
<tr>
<td>Crusader® (post-em.)</td>
<td>500 mL</td>
<td>B</td>
<td>0.0</td>
</tr>
<tr>
<td>Avadex® Xtra (pre-em.) + Hussar® (post-em.)</td>
<td>1.6 L + 200 g</td>
<td>J + B</td>
<td>0.3</td>
</tr>
<tr>
<td>Avadex® Xtra (pre-em.) + Atlantis® (post-em.)</td>
<td>1.6 L + 330 mL</td>
<td>J + B</td>
<td>0.0</td>
</tr>
<tr>
<td>Avadex® Xtra (pre-em.) + Judgement® 90 (SST)</td>
<td>1.6 L + 1.875 L</td>
<td>J + Z</td>
<td>0.0</td>
</tr>
<tr>
<td>Atlantis® (post-em.) + Judgement® 90 (SST)</td>
<td>330 mL + 1.875 L</td>
<td>B + Z</td>
<td>0.0</td>
</tr>
<tr>
<td>Hussar® (post-em.) + Judgement® 90 (SST)</td>
<td>200 g + 1.875 L</td>
<td>B + Z</td>
<td>0.0</td>
</tr>
</tbody>
</table>

SST, Selective spray-topping late post-emergence to prevent seed production.

There are, however, some cases of multiple resistance to all three post-emergent herbicide groups, for which the data in Table 23 would be irrelevant because no post-emergent option would be effective (refer to Table 24 instead). Reliance solely on pre-emergent herbicides would result in populations of wild oats increasing. Surviving plants from trifluralin and Avadex® Xtra (triallate) treatments tend to be large and produce more seed than is lost from the germination process.

The major step of changing crops may open the door to the use of other herbicides (Table 24). Although this wild oat population can be well managed in wheat with pre-emergent herbicides + Atlantis® (mesosulfuron-methyl), alternative crops can be grown with better weed-control outcomes. Chickpeas grown on conventional row spacing or wide rows resulted in excellent control and with the use of herbicides that have probably not been used for many years. The inter-row spraying of Gramoxone® (paraquat) in wide-row chickpeas was successful, and the inclusion of simazine, trifluralin and Avadex® Xtra (triallate) as a pre-emergent option was useful.
Table 24: Controlling multiple resistance in wild oats (Groups A, B and Z).

<table>
<thead>
<tr>
<th>Crop</th>
<th>Treatments</th>
<th>Herbicide MoA group(s)</th>
<th>No. of wild oat seeds per m²</th>
<th>Yield (t/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TT Canola</td>
<td>Trifluralin + Avadex® Xtra + atrazine + Sertin®</td>
<td>D + J + C + A</td>
<td>0.5</td>
<td>0.82</td>
</tr>
<tr>
<td>Canola</td>
<td>Trifluralin + Avadex® Xtra + Dual Gold® + Sertin®</td>
<td>D + J + K + A</td>
<td>15</td>
<td>0.82</td>
</tr>
<tr>
<td>Clearfield® canola</td>
<td>Intervix®</td>
<td>B</td>
<td>469</td>
<td>0.41</td>
</tr>
<tr>
<td>Chickpea 35-cm row</td>
<td>Trifluralin + Avadex® Xtra + Simazine + Sertin®</td>
<td>D + J + C + A</td>
<td>1</td>
<td>1.24</td>
</tr>
<tr>
<td>Chickpea 75-cm row</td>
<td>Trifluralin + Avadex® Xtra + simazine + Gramoxone®</td>
<td>D + J + C + L</td>
<td>11</td>
<td>0.87</td>
</tr>
<tr>
<td>Wheat</td>
<td>Trifluralin + Avadex® Xtra + Atlantis®</td>
<td>D + J + B</td>
<td>14</td>
<td>0.94</td>
</tr>
<tr>
<td>Wheat</td>
<td>Sakura® + glyphosate</td>
<td>B + M</td>
<td>35</td>
<td>1.08</td>
</tr>
<tr>
<td>Long fallow</td>
<td>Flame® + glyphosate</td>
<td>B + M</td>
<td>5</td>
<td>N/A</td>
</tr>
</tbody>
</table>

This population had confirmed complex resistance to Groups A, B and Z, however it was shown in previous trials to be partly susceptible to Atlantis® and Sertin®, hence their inclusion.

The same principle applied when growing canola with the inclusion of atrazine, trifluralin, Avadex® Xtra (triallate) and Dual Gold® (S-metolachlor).

Long-fallowing of paddocks is another alternative. The Flame® (imazapic) treatment did not control wild oats well and a follow-up application of glyphosate was required to prevent seedset.

Poor control of wild oats was reported in Clearfield® canola after using Intervix® (imazamox + imazapyr). The population may exhibit some resistance to this herbicide without treatment history because its high levels of resistance to Hussar® (iodosulfuron-methyl) (also Group B) may confer other Group B herbicide resistance. This is a likely reason why Flame® (imazapic) did not work well in the fallow.

Despite the failure of Clearfield® canola, Roundup Ready® canola should be more successful because the wild oat population seems susceptible to glyphosate. In one experiment at Edgeroi that was infested with a population resistant to Groups A, B and Z, wild oat seed production was almost completely prevented with one application of glyphosate. A potential problem with this choice is increased risk of glyphosate-resistant annual ryegrass.

In north-western New South Wales, chickpeas are a crop under threat from herbicide-resistant wild oats. Although various post-emergent selective grass herbicides are registered, all are Group A herbicides. Herbicides such as Hussar®, Atlantis® and Judgement® (flamprop-m-methyl) are not registered for use as they are in wheat. The pre-emergent herbicides trifluralin and Avadex® Xtra are options worth considering, and the inclusion of simazine could improve the control. However, if Group A resistance is present, then growing of chickpeas would be reliant on pre-emergent herbicides, with in-crop options limited to inter-row tillage or wick wiping.

There are two issues with relying solely on pre-emergence herbicides in chickpeas:
- Pre-emergent herbicides usually result in only 60–80% control under favourable conditions. They are not as effective as post-emergent herbicides (85–95% control).
- Chickpeas do not compete well with weeds, allowing the survivors of pre-emergent treatments to develop into large plants capable of large seed production.
Numerous tactics can be employed to reduce the impact of wild oats. These are summarised in Table 25 and could be used in combination as an IWM approach to maintain the usefulness of effective herbicides.

**Table 25: Tactics that could be used to manage wild oats.**

<table>
<thead>
<tr>
<th>Tactic</th>
<th>Likely to control wild oats (%) (range)</th>
<th>Ease of incorporation into farming system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crop choice and sequence</td>
<td>95 (30–99)</td>
<td>Easy to moderate</td>
</tr>
<tr>
<td>Improving crop competition</td>
<td>70 (20–99)</td>
<td>Easy to moderate</td>
</tr>
<tr>
<td>Herbicide-tolerant crops</td>
<td>90 (80–99)</td>
<td>Easy</td>
</tr>
<tr>
<td>Burning crop residues</td>
<td>40 (0–80)A</td>
<td>Moderate to hard</td>
</tr>
<tr>
<td>Inversion ploughing</td>
<td>50 (40–60)A</td>
<td>Moderate to hard</td>
</tr>
<tr>
<td>Autumn tickle</td>
<td>40 (30–60)</td>
<td>Easy to moderate</td>
</tr>
<tr>
<td>Fallow and pre-sowing cultivation</td>
<td>40 (0–80)A</td>
<td>Easy to moderate</td>
</tr>
<tr>
<td>Knockdown herbicides for fallow and pre-sowing control</td>
<td>80 (70–90)</td>
<td>Easy</td>
</tr>
<tr>
<td>Double knockdown (double-knock)</td>
<td>99 (99–100)A</td>
<td>Easy to moderate</td>
</tr>
<tr>
<td>Pre-emergence herbicides</td>
<td>80 (70–90)</td>
<td>Easy to moderate</td>
</tr>
<tr>
<td>Selective post-emergent herbicides</td>
<td>80 (70–90)</td>
<td>Easy</td>
</tr>
<tr>
<td>Spray-topping with selective herbicides</td>
<td>90 (60–99)</td>
<td>Easy</td>
</tr>
<tr>
<td>Crop-topping with non-selective herbicides</td>
<td>30 (10–50)A</td>
<td>Easy</td>
</tr>
<tr>
<td>Pasture spray-topping</td>
<td>80 (70–90)</td>
<td>Moderate</td>
</tr>
<tr>
<td>Silage and hay—crops and pastures</td>
<td>97 (95–99)</td>
<td>Moderate to hard</td>
</tr>
<tr>
<td>Renovation crops—green or brown manuring, mulching, etc.</td>
<td>95 (85–99)A</td>
<td>Moderate</td>
</tr>
<tr>
<td>Grazing—actively managing weeds in pastures</td>
<td>75 (60–80)</td>
<td>Moderate to hard</td>
</tr>
<tr>
<td>Weed seed collection at harvest</td>
<td>70 (20–80)</td>
<td>Hard</td>
</tr>
<tr>
<td>Sow weed-free seed</td>
<td>85 (50–99)A</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

Source: Integrated Weed Management in Australian Cropping Systems (A training resource for farm advisors), Section 6: Weeds, weed 1 annual ryegrass (p. 75) and weed 18 wild oats (p. 200). Eds T McGillion, A Storrie

A Estimated; not available in IWM manual. 91

### 3.4.6 Sweet summer grass

The first population of glyphosate-resistant sweet summer grass, found near Emerald, central Queensland in 2014, could survive rates of glyphosate of 450 mL to 2 L/ha, 28 days after application. The registered rates of application for moderate-sized plants are 800 mL to 1.6 L/ha. Rates as low as 250 mL/ha of glyphosate have controlled susceptible populations under glasshouse conditions. The resistant population appears to have at least an eight-fold level of resistance because the extent of control with 250 mL/ha on a susceptible population was slightly higher than the response of 2 L/ha on a resistant population.

Growers in central Queensland need to consider and use alternative control options for this weed to prevent or minimise the development of further glyphosate-resistant cases. Plants grown under glasshouse conditions are likely to be more susceptible to herbicides, and it is likely that glyphosate rates >2 L/ha may not be sufficient to control glyphosate-resistant sweet summer grass in the field, especially under less favourable conditions. 92

3.4.7 Awnless barnyard grass

Prior to summer 2011–12, there were 21 cases of glyphosate-resistant awnless barnyard grass. Collaborative survey work was conducted by NSW DPI, (the then) DAFF Qld and NGA in summer 2011–12 with a targeted follow-up in 2012–13. Agronomists from the Liverpool Plains to the Darling Downs and west to areas including Mungindi collected awnless barnyard grass samples that were tested at the Tamworth Agricultural Institute with Glyphosate CT at 1.6 L/ha at mid-tillering growth stage.

The key result from this survey was that the number of ‘confirmed’ glyphosate-resistant awnless barnyard grass populations had nearly trebled.

Residual herbicides (fallow and in-crop)

Several active ingredients are registered in summer crops, for example, S-metolachlor (Dual Gold®) and atrazine; or in fallow imazapic (Flame®) that provide useful management of awnless barnyard grass. The new fallow registration of isoxaflutole (e.g. Balance®) can provide useful suppression of awnless barnyard grass but has stronger activity against other problem weed species.

Double-knock control

This approach uses two different tactics applied sequentially. In reduced-tillage situations, this is frequently glyphosate first, followed by a paraquat-based spray as the second application or ‘knock’. Trials so far have shown that glyphosate followed by paraquat gives effective control even on glyphosate-resistant awnless barnyard grass. Note that the most effective results will be achieved from paraquat-based sprays by using higher total application volumes (100 L/ha) and finer spray quality and by targeting seedling weeds.

Several Group A herbicides such as haloxyfop (e.g. Verdict®) and clethodim (e.g. Select®) are effective against awnless barnyard grass but should be used in registered summer crops (e.g. mungbeans). Even on glyphosate-resistant awnless barnyard grass, a double-knock of glyphosate followed by paraquat is an effective tool. In the same situations, there has been little benefit from a Group A followed by paraquat application. (Note that Group A herbicides are more sensitive to moisture stress in awnless barnyard grass.) Application on larger mature weeds can result in very poor efficacy.

Timing of the paraquat application for awnless barnyard grass control has generally proven flexible. The most consistent control is obtained from a delay of three to five days, when lower rates of paraquat can also be used. Longer delays may be warranted when awnless barnyard grass is still emerging at the first application timing; shorter intervals are generally required when weeds are larger or moisture stress conditions are expected. High levels of control can still be obtained with larger weeds but paraquat rates will need to be increased to 2.0 or 2.4 L/ha. 93


3.4.8 Flaxleaf fleabane

Glyphosate resistance has been confirmed in flaxleaf fleabane. There is a large amount of variability in the response of fleabane to glyphosate, with many samples from non-cropping areas still well controlled by glyphosate, whereas increased levels of resistance are found in fleabane from reduced-tillage cropping situations.

Residual herbicides (fallow and in-crop)

One of the most effective strategies to manage fleabane is the use of residual herbicides in-fallow or in-crop. Trials have consistently shown good levels of efficacy from a range of residual herbicides commonly used in sorghum, cotton, chickpeas and winter cereals.

At least three registrations are available for residual fleabane management in fallow:

- residual (and knockdown) in-fallow—FallowBoss™ TORDON™ (2,4-D + picloram + aminopyralid) at 700 mL/ha + atrazine (600 g/L) at 3–5 L/ha, at least four months prior to planting sorghum
- residual control only—Balance® (isoxaflutole) at 100 g/ha
- residual control only—Terbyne® (terbutylazin) at 1.0–1.4 kg/ha.

Prior to 2012, diuron was the most consistent residual herbicide option for fleabane management, but non-crop use has been halted by the Australian Pesticides and Veterinary Medicines Authority.

Additional product registrations for in-crop knockdown and residual herbicide use, particularly in winter cereals, are being sought. A range of commonly used winter cereal herbicides have useful knockdown and residual fleabane activity. Trial work to date has indicated that increasing water volumes from 50 to 100 L/ha may help the consistency of residual control, with application timing to ensure good herbicide–soil contact also important.

Knockdown herbicides (fallow and in-crop)

Group I herbicides have been the key products for fallow management of fleabane, with 2,4 D amine the most consistent herbicide evaluated. Despite glyphosate alone generally giving poor control of fleabane, trial work has consistently shown a benefit from tank mixing 2,4-D amine and glyphosate in the first application. Registrations for knockdown management in the fallow or crop are as follows.

Knockdown in fallow:

- Amicide® Advance at 0.65–1.1 L/ha + Roundup® Attack at a minimum of 1.15 L/ha, followed by Nuquat® at 1.6–2.0 L/ha
- FallowBoss™ TORDON™ at 700 mL/ha + Ripper® (480 g glyphosate/L) at 1.5–2.25 L/ha (can also be followed with Spray.Seed® at 1.6 L/ha as a double-knock)
- Tordon® 75-D (2,4-D + picloram) at 0.7 L/ha + glyphosate
- Sharpen® (saflufenacil) at 17–34 g/ha + Bonza® at 1% + Roundup® Attack™ at a minimum of 115 L/ha (only up to six-leaf stage).

Knockdown in crop:

- Amicide® Advance at 1.4 L/ha (winter cereals)
- FallowBoss™ TORDON™ at 300 mL/ha (winter cereals).

Double-knock control

The most consistent and effective double-knock control of fleabane has included 2,4-D in the first application followed by paraquat as the second. Glyphosate alone followed by paraquat will result in high levels of leaf desiccation but plants will nearly always recover.

Timing of the second application in fleabane is generally aimed at approximately 7–14 days after the first application. However, the interval to the second knock appears quite flexible. Increased efficacy is obtained when fleabane is actively growing or if
Rosette stages can be targeted. Although complete control can be obtained in some situations, control levels will frequently only reach approximately 70–80%, particularly when targeting large flowering fleabane plants under moisture-stressed conditions. The high cost of fallow double-knock approaches and inconsistency in actual control level of large mature plants is a key reason why proactive fleabane management should be focused at other growth stages.  

### 3.4.9 Feathertop Rhodes grass

#### Residual herbicides (fallow and in-crop)

Feathertop Rhodes grass is generally poorly controlled by glyphosate alone even when sprayed under favourable conditions at the seedling stage. Trial work has shown that residual herbicides generally provide the most effective control, a similar pattern to that seen with fleabane. Many currently registered residual herbicides are being screened and offer promise in both fallow and in-crop situations. The only product currently registered for feathertop Rhodes grass control is Balance® (isoxaflutole) at 100 g/ha for fallow use.

#### Knockdown herbicides (in-crop)

Currently, the only registrations for knockdown of feathertop Rhodes grass are the use of Group A herbicides in cotton, mungbean and other broadleaf summer crops.

#### Double-knock control

A double-knock of glyphosate followed by paraquat is a very effective strategy against awnless barnyard grass; however, the same approach is variable and generally disappointing for feathertop Rhodes grass management.

By contrast, a small number of Group A herbicides (all members of the ‘fop’ class) can be effective against feathertop Rhodes grass but they need to be managed within several constraints. Although they can provide high levels of efficacy on fresh and seedling feathertop Rhodes grass, they need to be followed by a paraquat knock to achieve consistent, high levels of final control.

Group A herbicides carry a high risk of selection for resistance, again requiring follow-up with paraquat.

Group A herbicides generally have narrower windows for successful use in terms of weed growth stage than herbicides such as glyphosate, and will generally give unsatisfactory results on flowering and/or moisture-stressed feathertop Rhodes grass.

Not all Group A herbicides are effective on feathertop Rhodes grass.

Many Group A herbicides have plant-back restrictions to cereal crops.

A permit (PER12941, expiry 31 August 2019) has been issued, in Queensland only, for the control of feathertop Rhodes grass in summer fallow situations prior to planting mungbean. It covers the use of Verdict at 150 mL/ha followed by paraquat at a minimum of 1.6 L/ha, within 7–14 days after the first application. First application should be between weed growth stage three-leaf and early tillering.

Timing of the second application for feathertop Rhodes grass is still being refined but application at approximately 7–14 days generally provides the most consistent control. Application of paraquat at shorter intervals can be successful, when the Group A herbicide is translocated rapidly through the plant, but this has resulted in more variable control in field trials. Good control can often be obtained up to 21 days after the initial application.  

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3.4.10 Windmill grass

Glyphosate resistance has been confirmed in windmill grass.

Residual herbicides (fallow and in-crop)

Preliminary trial work has shown a range of residual herbicides with useful levels of efficacy against windmill grass. These herbicides have potential for both fallow and in-crop situations. As at 2014, no products are registered for residual control of windmill grass.

Double-knock control

Similar to feathertop Rhodes grass, a double-knock of a Group A herbicide followed by paraquat has provided clear benefits compared with the disappointing results usually achieved by glyphosate followed by paraquat. Similar constraints apply to double-knock for windmill grass control as for feathertop Rhodes grass.

Although some Group A products can provide high levels of efficacy on fresh and seedling windmill grass, they need to be followed by a paraquat knock to get consistent high levels of final control. Their high risk of selection for resistance also necessitates follow up with paraquat.

Because Group A herbicides generally have limited opportunities for successful use in terms of weed growth stage compared with herbicides such as glyphosate, they will generally give unsatisfactory results on flowering and/or moisture-stressed windmill grass.

Many Group A herbicides have plant-back restrictions to cereal crops.

A permit (PER13460, expiry 31 March 2022) has been issued, in New South Wales only, for the control of windmill grass in summer fallow situations. It is for quizalofop-p-ethyl (e.g. Targa® 99.5 g a.i./L) at 0.5–1.0 L/ha followed by paraquat at a minimum of 1.6 L/ha, within seven days after the first application. Use of 200 g a.i./L of quizalofop-p-ethyl formulations is also permitted at 0.25–0.5 L/ha. First application should be at growth stages between three-leaf and early tillering.

Timing of the second application for windmill grass is still being refined; however, application at approximately 7–14 days generally provides the most consistent control. Application of paraquat at shorter intervals can be successful, when the Group A herbicide is translocated rapidly through the plant, but has resulted in more variable control in field trials and has been clearly antagonistic when the interval is one day or less. Good control can often be obtained up to 21 days after the initial application. 96

Group A herbicide plant-backs

Typically, Group A grass-selective herbicides are designed for use in broadleaf crops to control grass weeds selectively. However, the recent occurrence of difficult-to-control summer grass weeds including feathertop Rhodes grass and awnless barnyard grass (particularly with glyphosate resistance) has resulted in some growers choosing to apply Group A herbicides in fallow. Applying Group A herbicides in fallow is a high-risk practice for two reasons:

- Research has shown that it takes only six to eight years of repeated Group A use before resistance to this important herbicide group appears. Once resistance is present, the herbicide will no longer be effective as an in-crop application, and there are few alternatives. It is therefore important that Group A herbicides be preserved for their intended in-crop use.
- There are plant-back restrictions for cereal crops following the application of Group A herbicides. As such, Group A herbicides applied in fallow can result in crop damage. 97


3.5 Mixtures and sequences

3.5.1 Never cut the rate

Reducing the application rate of herbicides has been proven to increase selection pressure on a range of weeds. Any saving in chemical costs is significantly outweighed by the risk of the low dose hastening the evolution of herbicide resistance.

Mixing herbicides can slow the rate of herbicide resistance if chemicals from two MoA are mixed at full label rates.  

Improving glyphosate efficacy

Using higher label rates can often improve weed control. Weeds with weak glyphosate-resistance mechanisms can often be killed with higher label rates. Additionally, higher rates can help to counteract poor application, improve control of older plants and stressed plants, or overcome reduced efficacy caused by using poor-quality water or treating plants covered by dust. Higher label rates can also improve glyphosate activity in plants exposed to higher temperatures that can occur in early autumn or late spring.

3.5.2 Mixing order

Correct mixing order reduces the risk of products interacting in a way that may reduce their efficacy or affect the stability of the tank mix. Addition of multiple products to the spray tank must take place in a specific order to ensure that they can be adequately mixed through the solution according to their solubility and formulation type (Table 26).

Table 26: Chemical mixing guidelines.

<table>
<thead>
<tr>
<th>Mixing order</th>
<th>Water, chemical, additives</th>
<th>Examples of product</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Water conditioners, acidifiers, etc.</td>
<td>e.g. Bonus®, Liase®, Li 700*</td>
</tr>
<tr>
<td>2</td>
<td>Wettable, dispersible powders</td>
<td>e.g. Lusta®, Nugran®, Associate®</td>
</tr>
<tr>
<td>3</td>
<td>Dry flowable granules (WDG)</td>
<td>e.g. Diuron DF, Simazine DF</td>
</tr>
<tr>
<td>4</td>
<td>Flowables (suspension concentrates)</td>
<td>e.g. Simazine, diuron flowable</td>
</tr>
<tr>
<td>5</td>
<td>Wetter if using emulsifiable concentrates</td>
<td>e.g. Activator® 90, Chemwet 1000</td>
</tr>
<tr>
<td>6</td>
<td>Emulsifiable concentrates</td>
<td>e.g. Triflur® Xcel™, Avadex® Xtra, Estercide®</td>
</tr>
<tr>
<td>7</td>
<td>Water-soluble concentrates</td>
<td>e.g. Amicide®, Credit®, Glyphosate CT, Amicide®</td>
</tr>
<tr>
<td>8</td>
<td>Adjuvants</td>
<td>e.g. Chemwet 1000, oils, Li 700*</td>
</tr>
<tr>
<td>9</td>
<td>Liquid urea-ammonium nitrate</td>
<td>Easy N</td>
</tr>
</tbody>
</table>

Oils must be added last to all mixes. If Li 700® added at stage 1, do not add later. When adding water conditioner, fill spray tank as full as practical before adding any chemicals. There are some exceptions to these basic guidelines: (1) Glyphosate and some 2,4-D products (e.g. Surpass® 475, see extract from the Surpass® 475 label): add clean water, add water conditioners, add other herbicides, insecticides etc.; mix thoroughly; add 2,4-D product; fill the tank to ~95%; add glyphosate; add other adjuvants; add remaining water. (2) Glyphosate and Stari™ Advanced herbicide (refer to the Stari™ Advanced label): glyphosate is put in the spray tank before Stari™ Advanced.

Source: GRDC 100


3.6 Herbicide rotations

Repeated application of effective herbicides with the same MoA is the single greatest risk factor for the development of herbicide resistance. Rotating chemical groups, in combination with a range of other non-chemical tactics, is essential for reducing the risk of, or managing, herbicide resistance.

Although herbicide rotation is vital to countering the threat of resistance, it alone is not enough and needs to be used in conjunction with other resistance-management strategies.

Research in South Australia in 2013 into glyphosate and paraquat multiple resistance in ryegrass found that the populations evolved resistance through being sprayed almost exclusively with glyphosate and paraquat with no follow-up weed control in any form. All of these multiple-resistant populations were from situations where herbicides were the only form of weed control and herbicide rotation was the only form of IWM.

Researchers found that if the double-knock strategy had been used every year at lethal rates, resistance would have been a low probability. However, this ideal scenario was difficult to achieve in real situations.

Rotating between glyphosate and paraquat, then following up with other weed management, is likely to reduce or delay significantly the evolution of resistance. An additional benefit of this system is the reduction in the weed seedbank that will result. 101

3.7 Herbicide management

Research has shown that although glyphosate-resistant weeds are resistant at all growth stages, seedlings are more sensitive than multi-tillered plants. Numerous trials have shown that herbicide-resistant weeds are often killed or heavily damaged if treated at the seedling stage. A common strategy used by growers is to delay application of glyphosate to maximise germination from the seedbank in order to ‘treat all the weeds’. This strategy can be effective if the weeds are not herbicide-resistant or stressed. However, reduced control of older plants that are herbicide-resistant can occur if rates are not sufficiently high or weeds are stressed. In weed species that exhibit staggered germination, such as brome grass, wild oats and wild radish, multiple herbicide timings are recommended. The type of resistance mechanism(s) present and more importantly the level of resistance conferred can also influence glyphosate efficacy. 102

3.8 Farming practices

Where is resistance taking farming systems?

Experience from the southern grain regions of Australia, where resistance has been a major problem for more than 20 years, is that resistance makes grain production more complicated. Rotations need to change to introduce (or increase the frequency of) crops where control of the most problematic weeds can be maximised. Our thinking about weed control also has to change, with the focus on population management and seedset control, rather than killing weeds after they have emerged. Reducing seedbanks is an important strategy.

In the northern region, the fallow system is a weak link in weed management. Tactics such as double-knock and use of weed-detection sprayers are helping to manage resistance in fallows. However, these practices are reliant on herbicides and resistance is inevitable. The fallow phase will be the greatest challenge to sustainable weed management in the northern region.

What other techniques are available? In the short term there are few. Tillage is the obvious tactic that can be re-introduced for fallow management. However, although tillage can effectively remove troublesome weeds, it will inevitably bury weed seed through the soil profile. One of the advantages of no-till systems is that they leave weed seed on the soil surface where it is often easier to deal with, particularly with pre-emergent herbicides. Burying the weed seed also increases the probability of staggered germination events. Cultivating an area that was cultivated in the past few years will bring weed seed to the surface and stimulate germination. Therefore, whereas strategic tillage may have a place in weed management, it may lead to a requirement for ever more tillage.

Other physical tactics such as gas, steam or even microwaves are not available in a form that could be used in large-area grain production, and may never be practical. Harvest weed-seed control tactics require the weed seed to enter the harvester at harvest. Such techniques are suitable for some weeds only, and they cannot be usefully employed in a fallow.

Strategies such as mowing or rolling could be used for weed control, but a cover crop is required to provide the necessary competition against weeds. This sacrifices a potential cropping phase to weed management.

The value of robotics for weed management will be the ability to conduct weed management at any time, regardless of other activities being conducted. At present, most of the focus in robotics for weed control is on detecting individual weed seedlings and applying a herbicide to kill them. This will reduce the cost to growers of the herbicides they are using; however, resistance management requires stopping seedset. Robotics for weed control will become much more valuable if it can be coupled with non-chemical weed-destruction tactics.

No obvious silver bullet will solve the herbicide-resistance problem. Even if there were, use of a single tactic would likely lead to resistance, just as reliance on herbicides has resulted in herbicide resistance. Growers in southern Australia have understood that a diversity of practices is required to manage weed populations and that there must be a focus on reducing seedbanks. In the absence of a ground-breaking weed-control technology, herbicides will continue to be a major contributor to weed management for at least the next decade. To preserve this valuable tool, growers need to use it more wisely. For the northern region, residual herbicides must become a bigger part of the strategy to take pressure off the post-emergent products, and practices that stop weed seedset have to be developed and adopted. 103

3.8.1 Plant clean seeds

A study by AHRI on 74 farms across the Western Australian grainbelt showed that 73% of cleaned crop seed samples had some level of weed-seed contamination.

This means that many growers unknowingly introduce significant levels of weed and volunteer crop seeds into the farming system at seeding time, even when crop seed has been cleaned. Many of these weed-seed populations are resistant to a range of commonly used post-emergent herbicides. 104

The AHRI survey found that use of a gravity table led to the lowest levels of weed-seed contamination in grain samples across all crop types. A rotary screen and a combination of more than one cleaning method were next most effective, followed by sieves. Cleaning by external contractors produced better results than self-cleaning by growers. 105

Uncleaned crop seed samples can have almost 25 times more contamination than cleaned crop seed.

From a positive perspective, almost one-quarter of all cleaned crop seed samples in the study were weed-free. 106

To minimise crop seed contamination:

• Pick the best paddock for crop seed. Select paddocks well in advance and ensure effective weed control in the previous year to minimise seedset.
• Clean silos, trucks, and sowing and harvesting equipment to stop weed-seed carryover.
• Avoid adding weed seed to the seedbank unnecessarily. Delay sowing to allow adequate weed control.
• Consider crop type and variety. Some crops are more competitive and allow more choice of herbicide options for in-crop weed control.
• Determine weed-seed contamination in crop seed before sowing to allow time for seed cleaning.
• Clean crop seed by using an indented cylinder, sieves or a gravity table. A gravity table is the most effective cleaning method.
• Widespread herbicide resistance means weeds that survive the crop phase and set seed are likely to be resistant.
• Contaminated crop seed may introduce herbicide resistance into clean paddocks. 107

3.8.2 Employ crop competitiveness

Increased crop competition can be used to reduce the number of weeds that escape chemical treatment and reach seed set. Cultivar selection, narrow row spacing, stubble management, seeding rate, sowing date and early vigour all contribute to the ability of a crop to suppress weed germination, growth and seed production. 108

Competitive varieties are an integral part of IWM systems and should be considered when planning for weed control. Increasing seeding rates improves yield, with the crop outcompeting weeds, and reduces the number of weeds that set seed. 109

Crop competition is known to be a factor in reducing the germination and growth of fleabane. This was highlighted in a trial at Trangie Agricultural Research Centre in central-western New South Wales in 2011, where increasing the row space of Crusader wheat from 33 to 66 cm increased fleabane plant numbers by 120% in the stubble immediately after harvest (Figure 2). The trial showed that the effect of row space is real and measurable, and can add significantly to other weed-control practices. The trial showed no significant effect of seed rate on fleabane population post-harvest. Based on trial results and the practicalities of row spacing, the ideal setup seems to be ~25 cm for disc seeders and ~30 cm for tyne seeders for western areas, and potentially narrower for eastern areas, of the northern grains region. 110

Figure 2: Effect of row spacing on crop competition with fleabane: 66-cm row space increased fleabane population by 120% in fallow compared with 33-cm row space (l.s.d. at $P = 0.05$, 0.34), with no significant effect of seed rate (ppm$^2$) on subsequent fleabane population. 111

Simple computer simulations by QDAF determined the long-term impact on the weed seedbank of the currently promoted strategies to prevent development of herbicide resistance. These simulations, using locally derived data, showed that the most effective strategy was the combination of crop rotation (summer and winter crops), rotation of herbicide groups, and use of more competitive crops (Table 27). Rotation of herbicide groups alone was not sufficient to prevent rapid development of resistance.

The simulations used wild oats with a starting seedbank of 1000 seeds/m$^2$, of which 1% were resistant to Group A herbicides. The simulations were done for a five-year period.

Table 27: Simulated changes in wild oat seedbank following various strategies for five years, starting with 1000 seeds/m$^2$, of which 1% were resistant to Group A herbicides.

<table>
<thead>
<tr>
<th>Weed management strategy</th>
<th>Total seedbank (no of seeds/m$^2$)</th>
<th>Resistant seeds (no of seeds/m$^2$)</th>
<th>Resistant seeds (% of total seedbank)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous winter cropping with poorly competitive wheat, and continuous and exclusive use of Group A herbicides</td>
<td>55,000</td>
<td>54,500</td>
<td>99</td>
</tr>
<tr>
<td>Continuous winter cropping with more competitive wheat, and continuous and exclusive use of Group A herbicides</td>
<td>39,000</td>
<td>38,600</td>
<td>99</td>
</tr>
<tr>
<td>Continuous winter cropping with more competitive wheat, and continuous and exclusive use of Group A herbicides, plus autumn tickle with delayed sowing and knockdown herbicide pre-sowing</td>
<td>5,700</td>
<td>5,650</td>
<td>99</td>
</tr>
</tbody>
</table>

An east–west crop-row orientation in winter cereals gave substantially greater suppression of weeds in trials from Western Australia and northern New South Wales. Orienting crop rows at 90° to the direction of sunlight is done on the basis that the crop will intercept more sunlight (photosynthetically available radiation) than with north–south sowing, giving weeds less chance to develop in the crop inter-row. In winter when the sun is at a lower angle, this shading of the inter-row can confer advantages, particularly in southern latitudes.

Research conducted during 2002–05 at Merredin and Beverley, Western Australia (latitudes 31°–32°S), has shown yield advantages as well as weed suppression from east–west row orientation compared with north–south. Within wheat and barley crops oriented east–west, weed biomass (sown wild radish and annual ryegrass, averaged throughout all trials) was reduced by 51% and 37%, and grain yield increased by 24% and 26%. 113

At Bithramere near Tamworth, a trial was established in 2012 with two barley varieties, Hindmarsh and Skipper, and using a sown population of 44Y84 canola as a substitute weed. Row orientation and row spacing (30 v. 50 cm) were evaluated. An east–west row orientation conferred a reduction in sown weed biomass of 39% compared with north–south orientation. Skipper, being the more vigorous variety, reduced sown weed biomass relative to Hindmarsh at both orientations. The weed fumitory was also observed to be prolific in the north–south sowing but was reduced almost to nil in the east–west row orientation.


Row orientation had no significant impact on grain yield under high weed competition. When no weeds were present, the north–south orientation gave a yield improvement of 6% at row spacing of 30 cm and 7% at 50 cm. 114

Summer crop work in sorghum showed that row orientation had no effect in terms of yield. This is most likely because the sun is at a higher angle and because of the lower plant populations and wider rows (75 cm). Importantly, east–west sowing did not yield any less than north–south sowing, meaning it would be compatible with winter crop programs that use east–west orientation for weed control. 115 116

3.9 Herbicide susceptibility testing

Knowing which herbicide MoAs are still effective can avoid in-crop herbicide failures and allow growers to develop long-term weed-management plans.

Testing weeds that survive a herbicide application will help to diagnose any resistance problems and allow growers to deal with this issue before seedset in affected patches. Susceptibility testing is recommended as part of an integrated weed management (IWM) and monitoring strategy, as promoted by the national grains industry’s WeedSmart campaign, which is aimed at combating herbicide resistance (www.weedsmart.org.au). 117

Testing can be conducted by using test strips in the paddock or by sending plants or seeds to a commercial testing service.

In-situ testing

An in-situ test can be performed in a paddock following herbicide failure. The test should be done at the earliest opportunity, remembering that the weeds will be larger than when the initial herbicide was applied. Test strips should be applied by using herbicide rates appropriate to the current crop growth stage and weed size, plus a double rate. The test strips should only be applied if the weeds are stress-free and actively growing. To assess the level of control more accurately, conduct counts of weed plant before and after application. Green or dry plant weights can be measured for more accuracy.

Paddock tests can provide useful information but can be difficult to interpret owing to variable paddock conditions and the often increased size of weeds when test strips are applied after a spray failure.

Commercial testing

Commercial testing services grow and test weeds under glasshouse or shade-house conditions, thus removing climatic or paddock variability that may affect results. They are able to test easily several different herbicides at several rates and compare the results to standard susceptible and resistant biotypes sprayed at the same time.

There are two types of commercial resistance tests:
1. Seed test. Seed is collected and sent to the testing service. Results may take up to four to five months. Suitable for pre-emergent and post-emergent herbicides.
2. Quick-test®. Live plants are collected and sent to the testing services. Results are available within six weeks. Not suitable for pre-emergent herbicides.

115 L Serafin, G McMullen (2011). Targeting high yields in dryland grain sorghum in northern NSW: row direction, row spacing and plant population. GRDC Update, Goondiwindi
Which paddocks to test

Start with high-risk paddocks, i.e. those with heavy use of herbicides and few non-herbicide control techniques to prevent weed seedset. Test any paddock where herbicide resistance is suspected as the cause of a spray failure.

Table 28 provides a guide to the number of years that may elapse before a problem is likely to develop for the major herbicide groups. These do not need to be consecutive applications.

**Table 28: Number of years using a particular herbicide Mode of Action before herbicide resistance is likely to be a problem.**

<table>
<thead>
<tr>
<th>Herbicide MoA group</th>
<th>Years of application (typical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>4</td>
</tr>
<tr>
<td>A ‘fop’</td>
<td>6</td>
</tr>
<tr>
<td>A ‘clim’</td>
<td>8</td>
</tr>
<tr>
<td>C</td>
<td>10–15</td>
</tr>
<tr>
<td>D</td>
<td>10–15</td>
</tr>
<tr>
<td>E</td>
<td>&gt;15</td>
</tr>
<tr>
<td>F</td>
<td>10</td>
</tr>
<tr>
<td>G</td>
<td>&gt;15</td>
</tr>
<tr>
<td>H</td>
<td>10</td>
</tr>
<tr>
<td>I</td>
<td>&gt;20</td>
</tr>
<tr>
<td>K</td>
<td>&gt;15</td>
</tr>
<tr>
<td>L</td>
<td>&gt;15</td>
</tr>
<tr>
<td>M</td>
<td>&gt;12</td>
</tr>
</tbody>
</table>


When can plants be sampled?

Although plants can be sampled before a herbicide is applied (e.g. break of season), resistance is usually much better detected after herbicides have been applied and poor control is noticed. Sample patches of weed escapes that become apparent after a herbicide application; this is usually how resistance appears in the early stages. Collecting seed randomly from across the paddock will underestimate of the level of resistance present because resistant patches could easily be missed.

How to sample for testing

Consult the testing service for more details on seed collection for herbicide-resistance testing.

For a seed test, a sample of ~3,000 seeds of each weed is required to test multiple herbicide MoAs. This equates to about one cup of annual ryegrass seed or six cups of wild radish pods.

For a Quick-test®, for each herbicide to be tested, 50 plants are required if small with few tillers, or 20 larger, later stage tillering plants.

For more information on testing and sampling:


Seed test only: John Broster, Charles Sturt University, Wagga Wagga, NSW. Ph: 02 6933 4001, Fax: 02 6933 2924, Email: jbroster@csu.edu.au. 118
Testing for resistance mechanisms

Although it is possible to make some general predictions of the most common resistance mechanisms that will occur from specific types of herbicide use and the species, it is difficult to predict the resistance mechanism in any one population. This is where herbicide testing becomes useful—not so much to determine whether the population is resistant but to identify which herbicides are still effective. This will vary from paddock to paddock because different mixes of resistance mechanisms are selected depending on management history and the specific genetics of the weeds in each paddock. Therefore, a test conducted on a population from one paddock may not be a good predictor of what will happen in the adjacent paddock. 119

Genetic markers for herbicide resistance

A new herbicide-resistance test for weeds, under development at Charles Sturt University, Wagga Wagga, uses Diversity Arrays Technology (DArT) as a fast, robust and cheap method for herbicide-resistance testing. In a study to determine whether DArT could be used to detect herbicide resistance, the technology identified trifluralin-resistant annual ryegrass with 90% accuracy.

DArT analyses thousands of fragments of DNA (known as genetic markers) and matches individual fragments to specific plant traits. Once a trait has been successfully linked to certain markers, DArT can then be used to screen DNA rapidly for the presence of this trait and report its presence or absence. It has been successfully developed for wheat, rice and barley, but it has not previously been employed on weed species.

The successful application of DArT will allow for the rapid analysis of plant samples for herbicide resistance without expensive DNA sequencing, providing greater genetic information and faster results that will be cheaper than other methods. By using DArT to analyse plant DNA, herbicide-resistance testing could be completed in as little as three weeks, which may allow for in-season control measures to be employed, or longer term management strategies to be developed for the following season.

The test also has potential to screen weed seeds for resistance to multiple herbicides simultaneously. 120


Application

For detailed information on best practice spray application, see GRDC’s Spray Application GrowNotes™.

The manual provides information on how various spraying systems and components work, along with those factors that the operator should consider to ensure the sprayer is operating to its full potential.

It focuses on issues that will assist in maintaining the accuracy of the sprayer output while improving the efficiency and safety of spraying operations. It contains many useful tips for growers and spray operators.

Information includes sprayer set-up, including self-propelled sprayers, new tools for determining sprayer outputs, advice for assessing spray coverage in the field, improving droplet capture by the target, drift-reducing equipment and techniques, the effects of adjuvant and nozzle type on drift potential, and surface temperature inversion research.

Health and environmental effects

Food crops compete with up to 30,000 species of weeds, 3,000 species of nematodes (microscopic worms) and 10,000 species of plant-eating insects, as well as viruses, fungi, mites and mice.

Crop protection products, also known as herbicides and pesticides, are used in both conventional and organic farming to keep crops healthy and abundant by protecting them against pests, weeds and diseases.¹

Herbicides are one of the vital tools that help farmers grow healthy crops. They keep our food free from moulds, insects and poisonous by-products. Herbicides also benefit us in many other ways.

In terms of the environment, herbicides enable farmers to produce more crops per unit area with less tillage, thus reducing deforestation, conserving natural resources and curbing soil erosion. Herbicides are also critical for the control of invasive species and noxious weeds.

The safety of herbicides for consumers, users and the environment is based upon strict testing. Herbicide manufacturers take their product stewardship responsibilities and end-user training, very seriously.

Herbicides ensure that consumers have access to food that is safer, more nutritious, and more affordable than ever before. They combat global malnutrition and starvation and help low-income families in developed countries afford more fresh fruit and vegetables.

Herbicides are among the most rigorously regulated chemicals in the world, and re-registration processes ensure that their safety is frequently assessed based upon the latest scientific standards.²

5.1 Social and Health benefits

The United Nations Food and Agricultural Organisation estimates that pests cost developing nations billions of dollars in national income. The loss of food in farming communities contributes to malnutrition leading to the death of more than 12 million children annually. Herbicide use means a farmer does not need to manually weed their field which requires 6-7 days per 0.1 ha. If hand-weeding was the only option an additional 70 million workers would be required in the US alone. Greater quantities of available food in a community also means better nutrition and better health. With less manual labour and improved nutrition from successful harvests there is a better quality of life for those living in farming communities, slowing down the flow of people moving from rural areas to cities. Reduced requirements for manual labour gives farmers’ families the option to pursue education, rather than being forced into full time maintenance and weeding of crops.³

Before a product reaches the market, regulatory bodies balance potential risk to humans and the environment against projected economic, social and environmental benefits. If the risks are so great that benefits of any kind would not outweigh them the pesticide would not be registered for use.⁴

5.2 Regulation of pesticides and human health

Human health, worker safety and the protection of the environment are the highest priorities for the agricultural industry. The production and use of crop protection products in Australia is highly regulated to assure safety for users, consumers and the environment. 5

Almost every chemical or product, whether it is natural or manmade can potentially be unsafe. With the appropriate precautions and instructions for use, chemicals and products can be considered safe and be used safely by the public.

The products that farmers use today are subject to a rigorous risk assessment process. Industry is required to submit all information on the environmental and human health hazards associated with any product. The Australian Pesticides and Veterinary Medicines Authority (APVMA), then assesses whether all the risks to human health, worker safety and the environment are effectively controlled before the product is released to the Australian market. The onus is on the industry to demonstrate this to the satisfaction of the relevant regulator.

This is different to proving safety, as while all current evidence might point to a product being safe, new scientific evidence may emerge that alters that conclusion. Australian regulators frequently respond to up to date scientific information and either alter use conditions, or prohibit particular uses where the risk is too great. Under the Australian system no product is ever ‘proven safe’ and all products may be subject to new scientific evidence that questions their safety. Industry may even be required to generate additional information to further investigate potential hazards to human or environmental health. 6

5.3 Safe use of chemicals on farm

Farmers are not only responsible for their own safety when using chemicals on farm, but also the safety of their workers.

Some simple steps can help to ensure safe chemical handling all year round. These include:

- treating all chemicals with extreme caution and following instructions carefully;
- wearing protective clothing, covering exposed skin and wearing gloves, goggles and a face mask;
- applying chemicals only in suitable environmental and weather conditions;
- storing chemicals safely, out of children’s reach and away from seeds and fertilisers;
- undertaking training in the safe handling of agricultural and veterinary chemicals, in accordance with work health and safety legislation in your state;
- reporting any adverse events, such as unexpected crop damage or a reaction needing medical assistance, to the APVMA on 02 6210 4701;
- having a ready reference guide for local support services in the event of exposure. 7

5.3.1 Personal protection equipment (PPE)

Personal protection equipment (PPE) forms the basis for the safe handling of chemicals. Whenever a farmer is decanting, mixing or using chemicals, it is essential to wear appropriate PPE as described on the label. This equipment is used as a barrier to reduce the risk of chemicals entering the body. 8

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To determine what is required, growers should read the label and MSDS for required PPE, these may include:

- Long sleeve shirt and long trousers and/or overalls (Photo 1)
- Rubber boots
- Waterproof apron
- Nitrile gloves (carry a spare pair in the cab)
- Eye protection
- Disposable mask or respirator.  

![Photo 1: Good PPE clothing and gear.](Source: GRDC)

Preparation for spraying tips:

- Do not eat, drink or smoke while preparing and mixing chemicals.
- Always wash hands before going to the toilet, smoking or eating.
- Avoid contact with skin, eyes or mouth. If contamination occurs, wash the area with lots of water.
- Check weather conditions to determine Delta T value.
- Read the label and MSDS recommendations before you open a drum or package.
- Match the nozzle type and pressure according to weather conditions and chemical you are using and requirements of the label.
- Mix the chemical according to the correct mixing order.
- Be careful opening containers of concentrate, as pressure may build up inside causing them to spurt. Be aware when coupling or uncoupling self-filling devices, poor connections may cause chemical to splash.
- Safety glasses should be worn when pouring liquid concentrate into measuring jugs.
- When mixing wettable powders, stir carefully as dust can easily settle on exposed skin.
- After handling chemicals – wash your gloves with soap and water prior to removal to protect your hands from the residue left on them and then thoroughly wash your hands.
- Avoid wearing contaminated clothing in the tractor cab.

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• Keep windows, doors and vents closed and air conditioning on ‘recycle’ during spray operations. Normal air conditioning in tractor cabins or vehicles does NOT give you adequate protection.

• Wear gloves when cleaning blocked nozzles of handling parts of sprayers or pumps when spraying. Use a toothbrush or special brush to clean nozzles, DO NOT put in your mouth or blow to clear.  

5.3.2 Mixing chemicals
Mixing should be carried out in a well ventilated, well-lit and hazard-free area. Mix the chemicals according to the label directions. Only prepare enough for immediate use. Remember when mixing chemicals, you are handling the concentrate, which is more toxic than diluted mixtures. The risk of splashes and absorbing a high dose of chemical is usually greater when the chemical is in its concentrated form. Even though there may only be a small amount, it's still unsafe and should be handled with caution.  

5.3.3 Primary Industries Health and Safety Partnership (PIHSP)
The aim of the Primary Industries Health and Safety Partnership (PIHSP) is to undertake research and development activities that improve the:

• Physical health of farming and fishing workers and their families.
• Mental health of farming and fishing families.
• The safety of the work environment and practices in farming and fishing industries.

This program is funded by AgriFutures Australia, Grains Research and Development Corporation, Fisheries Research and Development Corporation, Australian Meat Processor Association, Meat & Livestock Australia, and the Cotton Research and Development Corporation.

The goal of this program is to improve the health and safety of workers and their families in the farming and fishing industries across Australia.

The Program covers physical and mental health and safety issues that are relevant to farming and farm families as well as those working in the fishing industry (both aquaculture and wild-catch sectors).

The key target audiences for health and safety information are business owners, managers and employees, who with their families live on Australian farms and in fishing communities.

The Program also works to improve consultation and communication with health professionals and researchers working in the field of rural health and safety.  

5.4 Environmental effects
Australia’s strong regulatory system ensures that all crop protection products, when used responsibly and in accordance with label instructions, present no unacceptable risk to the environment.

Additionally, manufacturers and users of crop protection products are also protecting the environment through stewardship activities and innovative application practices that seek to better target pests and minimise any adverse impact on the environment.

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5.4.1 Managing risk to the environment

Pesticide companies seeking to register a farm chemical must provide extensive research to the independent regulator, the APVMA, demonstrating that the product does not present any unacceptable risks to people, the environment or export markets when used according to the instructions on the label.

As part of the assessment, the APVMA seeks specialist advice on potential environmental impacts from the Australian Government Department of Sustainability, Environment, Water, Population and Communities and the Department of Health and Aging.

If a product is found to present no significant risks to people, the environment or export markets, the APVMA may register it for use in Australia. The APVMA also approves the way in which each product must be used, which is detailed on the label. By following the label, pesticide users can be assured they are managing any risks to human health and the environment while achieving maximum effect from the product. The label also provides instructions that help users minimise any drift of the chemical onto other crops or neighboring properties.

Any adverse or unintended results of pesticide use are reported to the APVMA through its Adverse Experience Reporting Program. The APVMA uses this information to decide whether an agricultural chemical should be restricted in use, withdrawn from sale or subject to an official review.

5.4.2 Protecting the environment

Crop protection products can also protect the environment by controlling insects and invertebrate pests, diseases and invasive plants so that native plants can thrive in their natural habitat.

Environmental benefits of pesticides include:

- Herbicides reduce the mechanical cultivation of fields in turn reducing the production of greenhouse gases, slowing down soil erosion and reducing moisture loss from soil surfaces.
- No till systems would be impossible without herbicides.
- Chemical weed control has been shown to reduce soil erosion by 400% (40 tonnes/ha) and does not affect soil health with long-term exposure to pesticides over 20 years shown to have no detrimental effect on soil microorganisms.
- Higher crop yields mean producing more on the same amount of land which reduces the pressure to cultivate uncropped land to increase production.

CropLife Australia members help to protect the environment by taking responsibility for their products from manufacture through to disposal. CropLife’s principal stewardship activities Agsafe Accreditation & Training, drumMUSTER, and ChemClear® ensure that products are developed, sold, used and disposed of appropriately.

Individual member companies also teach their customers how to use pesticides responsibly to protect the environment and neighbouring crops.

5.4.3 Drum and chemical disposal

drumMUSTER

drumMUSTERS provides Australian agricultural and veterinary chemical users with a recycling pathway for eligible empty agvet chemical containers. It provides an easy, environmentally-friendly way of disposing of empty farming chemical containers across rural Australia.

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drumMUSTER is funded by levies collected by AgStewardship, which was established to develop stewardship programs for Australia’s agriculture sector, along with ChemClear®.  

The drumMUSTERT containers are collected and transported by an approved team of processors and delivered to materials recovery centres where they are recycled into items such as wheelie bins, fence posts and garden stakes.

Disposing of empty agvet chemical containers in the right way is crucial to the reputation and sustainability of the agricultural industry in Australia. By using the drumMUSTERT recycling program you can turn your unwanted containers into useful, sustainable products rather than having them placed into landfill or building up on farm.

ChemClear®

ChemClear provides Australian agricultural and veterinary chemical users with a collection and disposal pathway for their unwanted chemicals.

The introduction of ChemClear has meant that waste holders can dispose of their eligible left-over chemicals at no additional cost.

ChemClear is a national product stewardship program and enjoys the support of 100 participating agvet chemical manufacturers and industry stakeholders, including grower and farming associations, local and state governments.

ChemClear compliments drumMUSTER, by providing agvet chemical users with a recycling and disposal option for agvet chemicals. Both programs are funded by AgStewardship Australia Limited through a 4 cents per litre levy placed on participating manufactures’ products and passed onto consumers at the point of sale.

ChemClear’s objective is to provide a safe disposal path for unwanted agricultural chemicals.

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5.5 Spray drift

The possibility of off-target spray drift accompanying the application of pesticides is a concern both to the community and the agricultural industry, for whom it is a constant challenge to find ways to effectively minimise drift. The APVMA is responsible for ensuring that off-target pesticide spray drift does not harm human health, the environment or Australia’s international trade.

Spraying agricultural chemicals, whether from the ground or the air, needs to be properly planned and carefully executed, to minimise the risk of off-target chemical movement.

As an agricultural chemical user, you have a legal obligation to ensure that the chemicals you apply stay within the target area.

It is an offence to undertake agricultural spraying which:
• injures any plants or stock outside of the target area
• injures any land outside the target area so that growing plants, or keeping stock on that land would result in contamination, or
• is likely to contaminate any agricultural produce derived from plants or stock outside the target area. 18

5.5.1 What is spray drift?

Spray drift is the most common cause of off-target chemical movement. It can injure or damage plants, animals, the environment or property, and even affect human health. ‘Drift’ is the airborne movement of agricultural chemicals as droplets, particles or vapour. 19

Almost every pass of the spray rig over a paddock will result in a small amount of the applied product remaining in the air after the spray has been released from the nozzles. When weather conditions are suitable for spraying, the majority of the product that has become airborne will usually settle back to the ground within a few hundred metres from where it was released, often in the same paddock. However, if too much of the product is left in the air due to poor nozzle choice, booms being set too high, spraying at high speeds or spraying during the wrong conditions, the consequences can be considerable. The off-target movement of spray that results in damage to a sensitive area or crop is always the result of poor planning or a bad decision by the spray operator. 20

5.5.2 Importance of managing spray drift

Additional to the financial incentive and legal requirements to maximise the amount of product reaching the target area, there are many reasons to minimise spray drift. These include:
• protection of human health – your family, neighbours and community;
• protection of trade by avoiding residues on crops and pastures, particularly where residue limits have not been established in the destination market;
• protection of farm vegetation, native vegetation, animal habitats and biodiversity;
• protection of water quality, including water for human consumption, stock use and irrigation;
• protection of aquatic organisms
• protection of beneficial insects (predators and pollinators) and their refuges.

To reduce these potential impacts, it is important for the spray operator to be able to make changes when required. This necessitates the ability to interpret information,
Section 5
HERBICIDE USE

5.5.3 Spray drift management

10 steps to minimize spray drift

Operate within the weather guidelines and adopt the following practices to reduce spray drift risk.

1. Ensure that the spray droplet spectrum is optimised to maximise efficacy and minimise the opportunity for droplets to evaporate down to drift-prone size before reaching the target. Use the coarsest droplets possible and avoid wetters that increase drift potential.

2. Operate machinery at optimum speed to maximise the boom's stability and minimise the machine's aerodynamic effect on airflow behind the machine and boom.

3. Keep the boom height as low as possible to reduce the time that droplets are in the air and to take advantage of lower wind speed normally experienced near the surface.

4. Plan ahead and be prepared to adjust operations to combat weather variations.

5. Be sure to take into account the local microclimatic conditions, especially at night.

6. Continually monitor conditions at the site and at a height representative of the spray zone and adjust operating practices for current conditions.

7. Use on-board weather stations, smoke devices or ribbons attached to booms and fence lines to assist in the detection of variations in wind direction and speed. If using smoke devices, be mindful that the initial smoke rise will be due to the inherent heat of the source.

8. Take extra care when applying pesticides over partially bare ground, which is hot and conducive to rapid evaporation and thermals.

9. Avoid spraying an hour before sunset if an inversion is likely and for an hour-and-a-half after sunrise if an inversion occurred overnight (variations of wind speed and direction are likely to be unpredictable).

10. Ensure that adequate buffers are maintained to protect sensitive areas.

Wind speed is critical

Air movement is needed to ensure that mixing occurs. This helps to deposit airborne droplets. Mixing of the air happens when air movement is more turbulent, especially while the sun is heating the ground. Day-time spraying – once the sun is up – when the wind speed is consistently above 4-5 km/h is usually safer than night-time spraying – between sunset and sunrise.

It has been suggested that night-time wind speeds should be above 11 km/h to ensure some mixing occurs and to minimise the likelihood of a surface temperature inversion. Wind speeds should be below 15-20 km/h as measured at the site of application, depending on the label instructions.

Temperature and humidity (Delta T)

Delta T values indicate evaporative potential. High values can reduce droplet survival in the air and at the target. Airborne droplets will rapidly decrease in size when the delta T value of the air exceeds 8 to 10. When using a coarse spray quality or larger, also check the Delta T value at the target and avoid values above 10 to 12. Low Delta
T values (Figure 1) encourage droplet survival, which can increase the risk of spray drift. Using the coarsest droplets that will provide efficacy will reduce the airborne fraction and increase droplet survival times.  

Figure 1: The relationship of Delta T to relative humidity and temperature. A common spray guideline is to spray when Delta T is between 2 and 8; with caution below 2 or above 10.

Spray quality

Spray quality is a useful guide for determining the amount of chemical that could remain in the air after the spray has been released from the nozzle. Coarser spray qualities reduce risk by reducing the airborne fraction. Each time spray quality is changed to a larger classification (for example from medium to coarse), the amount of spray that exists as droplets capable of moving off target is halved.

Nozzle height and travel speed

Nozzle height should not be more than that required for double overlap at the top of the stubble or crop/weeds canopy (whichever is taller). Consider using auto-height control, suitable touch-down wheels, or lower travel speeds to improve boom stability and to assist with minimising boom height (Photo 2). Increasing height from 50 cm above the target to 70 cm can increase the amount of chemical left in the air by up to 4 times. Increasing height from 50 cm to 1 metre can increase the airborne fraction by up to 10 times. Increasing travel speeds will increase the amount of chemical left in the air. This can be due to detrainment at the nozzle (escape of small droplets from the pattern) or aerodynamic affects around the sprayer itself. Increased travel speeds interact with increased wind speeds.

Applicators should avoid travel speeds above 16 to 18 km/h unless there is excellent boom height control and equipment is set up to minimise airborne droplets (that is, coarse spray quality or larger).

**Vegetative and buffer zones**

A buffer zone is an area around a sensitive area in which agricultural chemicals should not be applied. The presence of a buffer zone allows spray drift to settle out of the air stream as it travels across the buffer zone before reaching the sensitive area. Prior to undertaking spraying, you should assess the risks and determine an appropriate buffer zone, as it will change from paddock to paddock and from year to year. 25

Leaving an unsprayed, downwind buffer between the treated area and sensitive areas can reduce the risk of damage from direct droplet deposit and may be a requirement on some labels. Porous vegetative buffers, such as Casuarina species, that are more than 1.5 times the release height can further reduce that risk, when the air flow is turbulent. However, under surface temperature inversion conditions vegetation may simply divert airborne droplets, rather than filtering them out. 26

**Managing sensitive areas**

Managing sensitive areas requires a thorough knowledge of what is around the area to be sprayed. Often this requires good communication with neighbours about what they have planted, or are planning to plant. It also requires the operator to do a bit of research. It is a good idea to talk to local advisers, who have knowledge about other crops in the area, and to access websites that may assist in identifying other sensitive areas. 27

Choose a chemical formulation that is less likely to drift off-target (e.g. use amine formulations of 2,4-D instead of 2,4-D high volatile esters which are more prone to drift as vapour during or after application). 28

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Useful websites include:

- Cotton Map.
- Bee Aware.
- Google Earth – for rivers, streams and drainage patterns within your local catchment.

Other useful information may be obtained by:

- acquiring detailed maps of neighbouring properties
- following label requirements and other technical information from product manufacturers; and
- accessing training and participating in stewardship programs.

Having identified potential sensitive areas, spray applicators need to consult label instructions for possible spray-drift restraints, downwind buffers and no-spray zones, and other directions for use, such as withholding periods.  

### 5.5.4 Surface temperature inversions

Key points:

- It is unsafe to spray where surface temperature inversion conditions are occurring, due to the potential risk of spray drift.
- Spray applied at dawn, dusk and during the night is likely to be affected by a surface temperature inversion.
- During surface temperature inversions, air near the ground lacks turbulence. This can lead to airborne pesticides remaining at high concentrations in the air at or near the surface.
- The direction and distance that pesticides can move in the air close to the ground is very hard to predict when surface inversions exist.

Inversions refer to when the air at the ground level becomes cooler than higher air. Unlike warm air that rises, cool air is dense and remains at the surface. Sprays applied in these conditions can become trapped in this cool air layer. Once trapped, they can move in different directions than indicated by the general weather pattern.

Inversion conditions can differ significantly from the broader forecast weather patterns. During the night, the ground loses heat and the low-level air cools (Figure 2). This results in air temperature increasing with height and the temperature profile is said to be inverted. When this occurs close to the ground it is called a surface temperature inversion. In a surface temperature inversion, the point where the temperature stops increasing and begins to decrease is the top of the inversion layer. When a strong surface temperature inversion has established, it can act like a barrier, isolating the inversion layer from the normal weather situation, especially the normal wind speed and direction.

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Surface temperature inversion conditions are unsafe for spraying as the potential for spray drift is high. In cooling night conditions, airborne herbicides can concentrate near the surface and unpredictable winds can move droplets away from the target. Pesticides trapped within a surface temperature inversion will tend to remain suspended within the inversion, typically moving to places wherever the relatively slow-moving air within the inversion layer ends up. This movement is likely to continue until the inversion breaks, which releases the trapped droplets. Often the air movement during an inversion will be towards the lowest part of the catchment, but as the inversion breaks the released droplets have the potential to go in almost any direction.

Confirming the presence of a surface temperature inversion with measurements is difficult, so growers must rely on visual clues that indicate if the atmosphere is stable. Smoke pots and smoking devices fitted to the sprayer’s exhaust can help indicate if the atmosphere has become stable or the wind has become less turbulent, which are strong indicators that a surface temp inversion may have formed. Other tools such as on-board weather stations or simple tell-tale flags placed in the line of sight can indicate if the wind has dropped out.

A surface temperature inversion is likely to dissipate after sunrise when the air temperature has risen by more than 5°C above the overnight minimum and wind speed is constantly above 7 km/h for more than 45 minutes (Photo 3). 30

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Photo 3: Under a surface temperature inversion air can separate into very stable layers (laminates) that can concentrate and transport airborne pesticides.

Source: Bill Gordon, GRDC.

5.5.5 The GRDC Spray Application GrowNotes™

The GRDC Spray Application manual provides information on how various spraying systems and components work, along with those factors that the operator should consider to ensure the sprayer is operating to its full potential.

This new manual focuses on issues that will assist in maintaining the accuracy of the sprayer output while improving the efficiency and safety of spraying operations. It contains many useful tips for growers and spray operators.

The manual uses scientific research to provide practical information on sprayer set-up, including:

- self-propelled sprayers,
- new tools for determining sprayer outputs,
- advice for assessing spray coverage in the field,
- improving droplet capture by the target,
- drift-reducing equipment and techniques,
- the effects of adjuvant and nozzle type on drift potential, and;
- surface temperature inversion research.

The manual comprises 23 modules and each of these features a series of videos to deliver advice to growers and spray operators in a visual, easy-to-digest manner.  


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Labelling and training

When spraying, growers must observe all label guidelines and permitted use patterns. This includes adhering to label instructions, application rates, withholding periods and safe operating procedures of the product being used.

It is critical to only use registered/permitted chemicals on crops and that any chemicals applied must be appropriately declared when delivering grain.

6.1 Labelling of chemicals

The highest risk for someone using a pesticide or any chemical, is not using the product according to label directions.

Pesticides are chemicals intended for preventing, destroying or controlling any pest—including unwanted species of plants, insects or animals. The term ‘pesticide’ can include products such as:

- herbicides e.g. weed sprays
- insecticides and larvicides e.g. insect sprays, repellents or baits
- vertebrate pest products e.g. baits, poisons or toxins
- biocides e.g. pool chemicals.

No matter which pesticide you use or where you use it, you should always read and understand the label instructions and use only as directed. Following the directions helps maximise the product’s effectiveness and minimises your risk of exposure to the chemical—while helping protect people, animals, crops and the environment.

When using a pesticide, always remember:

- if you cannot see the APVMA or NRA number on the label, it may not be registered and it could be dangerous – DO NOT use it
- if the label has been damaged, search the APVMA chemicals database or talk to your supplier to find the safety and use directions
- label instructions are legally binding—this includes the booklet if provided, do not use a product if you do not understand the label. 1

6.2 Reading a chemical label

It is essential that users read chemical labels before they begin applying a product. The sections below break down the components of an example label from a chemical drum.

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Model Pesticides Chemical Label

(1) CAUTION

KEEP OUT OF REACH OF CHILDREN. READ LABEL DIRECTIONS BEFORE USING.

(2) JO BLOGGS 500

(3) SELECTIVE HERBICIDE

(4) ACTIVE COMPONENTS: 50g/L. 1kg/ha rate is demonstrated set

(5) DIRECTIONS FOR USE

TREATMENT: BEST apply when soil is moistened with 6 hours. DO NOT apply in crops or weeds around to be treated or weedy conditions.

MEDIUM-DENSITY WETTING AGENT: This product can be used with a spreader-sticker which is registered for the herbicide category according to WHA. Complete instructions, including:

- EMERGING/STANDING PLANTS DO NOT SPRAY ON HOT DAYS OR DRY DAYS.

(6) PRECAUTIONS

- DO NOT SPRAY ON HOT DAYS OR DRY DAYS.

- DO NOT APPLY UNDER WET CONDITIONS.

- DO NOT APPLY WITH ANY COMBINATION OF SPRAYING EQUIPMENT THAT MAY AFFECT THE MIXTURE.

- DO NOT APPLY WITH ANY COMBINATION OF SPRAYING EQUIPMENT THAT MAY AFFECT THE MIXTURE.

- DO NOT APPLY WITH ANY COMBINATION OF SPRAYING EQUIPMENT THAT MAY AFFECT THE MIXTURE.
6.2.1 SECTION A: warnings and product description

A.1 The Signal Heading

- No signal heading: The chemical is ‘unscheduled’, and it is relatively safe to the person using the chemical. However, never treat any chemical lightly, as it may still affect our health, either in the short term or the long term.
- CAUTION The chemical is low to moderately hazardous to the person using the chemical. Often it can irritate the skin or eyes.
- POISON The chemical is very hazardous to the person using the chemical. It can cause poisoning if it enters a person’s body.
- DANGEROUS POISON. The chemical is extremely hazardous to the person using the chemical. Just a small amount of the chemical can cause poisoning and even death if it enters a person’s body. For these poisons there are usually restrictions on the purchase and use that are imposed by state or territory governments such as training and accreditation requirements.

Check with your state/territory coordinator and the APVMA website.

The signal heading also includes instructions to keep the product out of the reach of children, and to read the safety directions before opening or using the product.

A.2 Brand Name (or Trade Name)

The common name for the chemical product.

A.3 Type of Chemical

The broad description of what the chemical does. Common terms are:
- Herbicide = kills plants
- Insecticide = kills insects
- Fungicide = kills fungus diseases
- Nematicide = kills nematodes (tiny worm-like creatures, that usually live in the soil)
- Molluscicide = kills molluscs (slugs and snails).

A.4 Active Constituent

This is the name of the actual part of the chemical that does the work. That is, the part that kills the weeds or insects or other pests. The concentration of the active constituent is also given.
Some products contain a solvent to dissolve the active constituent. These solvents can sometimes be poisonous, and in such cases the amount and name of the solvent is shown on the label under the heading ‘Solvent’.

A.5 Resistance Group

To prevent the pest from building-up resistance to the chemical, you should not use chemicals from the same resistance group over and over. Swap between chemicals from different resistance groups.

Also see the information in section C.12 below.

A.6 What the Chemical Does

This lists the things that the chemical is registered to do. It includes which crops the chemical can be used on, and which insects, weeds, diseases, etc that it is registered to control.

A.7 Name, address and phone number of the business that made the chemical

Contact the business if you need advice on how to use the chemical and if you need other information about the chemical (for example, how to clean up spilled chemical). ²

6.2.2 SECTION B: directions and use

B.8 Restraints

This is a list of situations where the chemical MUST NOT be used; either because the chemical will not work in these situations or because it is too dangerous to use the chemical in these situations. Some chemicals do not have restraints. If spray drift restraints apply, including mandatory no-spray zones, they will be listed here. Drift margin instructions may include mandatory, legally enforceable instructions, such as:

- droplet size
- wind speeds when spraying
- surface inversion conditions
- record keeping
- downwind no-spray zones

B.9 Directions for use table

Information on how to use the chemical against specific pests on specific crops. Read the information in the table from left to right, making sure you read the information in all of the columns.

<table>
<thead>
<tr>
<th>CROP/SITUATION</th>
<th>PEST/WEED</th>
<th>STATE</th>
<th>APPLICATION RATE</th>
<th>WHP</th>
<th>CRITICAL COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lists the crops or situations where the product can be used.</td>
<td>Lists the pests or weeds that the products can control.</td>
<td>Lists the states where the product can be used.</td>
<td>Shows the rate or range of ratios that should be used to apply the chemical.</td>
<td>Lists the withholding period (WHP) for each crop.</td>
<td>Lists important application details for each crop.</td>
</tr>
</tbody>
</table>

B.10 ‘Not to be used for any purpose’ Statement

This statement is intended to limit the use of a product to purposes that have been assessed and approved by the APVMA. If you want to use a chemical in any way other than according to the label instructions, you may need to get a permit from the APVMA.

B.11 Withholding Period (WHP)

The time from when you apply the chemical, until you can pick the crop. You MUST NOT harvest a crop before the withholding period has expired. Some withholding periods may also apply to grazing of livestock on treated areas or cutting for stock feed.  

6.2.3 SECTION C: general instructions

C.12 Resistance Warning

These instructions should be followed, so that the insect, disease or weed does not become resistant to the chemical you are using (also see the information in section A.5 above).

C.13 Compatibility

This tells you if it is safe to mix the chemical with other chemicals. If chemicals are not compatible, they should not be mixed together. Contact your local agronomist and/or consultant for more information about compatibility with other chemicals.
C.14 Mixing Instructions
This is important information on how to mix the chemical with water. You must follow these instructions, otherwise the chemical may not work.

C.15 APVMA compliance instructions for mandatory droplet size categories
Any products that require application using mandatory droplet sizes will also include further mandatory instructions here.

6.2.4 SECTION D: precautions

D.16 Re-entry Period
The re-entry period is the time from when you apply the chemical, to the time when it is safe for you to go back into the treated area. If you want to go back into the treated area before this time, you must wear the recommended safety equipment.

D.17 Plant-back Period
The plant-back period is the time from when you apply the chemical, to the time when it is safe to plant seedlings or sow seeds into the treated soil. This applies to soil fumigants, and to some herbicides.

D.18 Protection of crops, native plants and other non-target plants
Describes the things you need to do (or not do) so that the chemical does not damage crops or other non-target plants.

D.19 Protection of Livestock
Describes the things you need to do (or not do) so that the chemical does not injure livestock (including bees).

D.20 Protection of wildlife, fish, crustaceans and the environment
Describes the things you need to do (or not do) so that your chemical does not damage the environment (damage to these is known as ‘off-target’ damage).  

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6.2.5 SECTION E: first aid and storage disposal

E.21 Storage and disposal
Information on how to safely store the chemical and how to safely get rid of empty containers. Note that chemicals must NEVER be kept in food or drink containers.

E.22 Safety directions
Information about how the chemical can affect your health, and what you should do to protect yourself from exposure to the chemical. It lists the safety equipment that you should wear when handling the chemical.

You should read the safety directions before opening the container or using the product.

More detailed safety information can often be found in the Material Safety Data Sheet (MSDS), which can be obtained from the company that made the chemical. Most MSDS can be downloaded from company websites. There are also other websites that provide this information.

E.23 First Aid
You should read and understand the first aid instructions on the label before you use the chemical, so that you know exactly what to do if there is an emergency.

The MSDS has much more detailed first aid instructions than the label, and often has advice for doctors. You should always have the MSDS on hand, and take it with you to the doctor or hospital if you believe you may be poisoned.

E.24 APVMA approval Number
In Australia, all farm chemicals MUST be approved by the Australian Pesticides and Veterinary Medicines Authority before they can be legally sold.

All registered products will have either an APVMA or NRA Approval Number on them. The APVMA approval number on a chemical label is our assurance that the product has been checked as safe and effective if we follow label instructions.
E.25 Batch number, Date of Manufacture (DOM), and expiry date

It is good to write down the batch number of all chemicals used, in case something goes wrong and the chemical does not work properly. Chemicals should not be used after their expiry date.

E.26 Dangerous goods/Hazardous chemical information

If a chemical container has a diamond shaped symbol on it (◊), the chemical is classified as a Dangerous Good and/or a Hazardous Chemical. Good and/or a Hazardous Chemical. If a product is classed as a Dangerous Good there are specific laws about how to transport and store it. Check with your chemical supplier to find out if you need to take special precautions when carrying Dangerous Goods on your vehicle when driving on public roads.

If the product is classified as a Hazardous Chemical you must comply with specific laws in relation to workplace health and safety aspects. 5

6.3 Maximum residue limits (MRLs) and Withholding periods (WHP):

The APVMA sets maximum residue limits (MRLs) for agricultural and veterinary chemicals in agricultural produce, particularly produce entering the food chain. These MRLs are set at levels that are not likely to be exceeded if the agricultural or veterinary chemicals are used in accordance with approved label instructions. At the time the MRLs are set, the APVMA undertakes a dietary exposure evaluation to ensure that the levels do not pose an undue hazard to human health. 6

Violations of MRLs affect the marketability of Australian export grain. By observing several precautions growers can ensure that grain coming off their farm is compliant. All Australian grain, whether destined for the domestic or export market, is tested for pesticide residue.

A single violation of an importing country’s MRL regulations can lead to punitive measures on all Australian grain exported to that country and undermine Australian grains’ reputation internationally. Consequences may include costs awarded against the exporter and/or grower. If repeated violations are detected with the same chemical, that chemical may be banned. 7

The withholding periods (WHPs) on a label are designed to provide users with the information they need to ensure that the food and fibre derived from treated crops and animals complies with the MRLs set by APVMA and Food Standards Australia New Zealand (FSANZ).

A withholding period (WHP) in relation to the use of a chemical product means the minimum period that needs to elapse between:

1. the last application of the product in relation to a crop, pasture or animal; and
2. the harvesting or cutting (including swathing), or the grazing of animals on the crop or pasture,

in order to ensure that the products residues fall to or below the maximum residue limit (MRL).

Withholding period statements are found on chemical product labels within or below the Directions for Use table.

The period of time for a WHP may be written in days, (i.e. 1 day, 14 days), or weeks (i.e. 3 weeks, 16 weeks), in a few case no time period may be given.


Examples of WHPs include:

**HARVESTING:**
- Not required when used as directed
- DO NOT harvest for 14 Days

**GRAZING:**
- DO NOT graze or cut for stock food for 14 days after application.
- DO NOT graze treated crops.

In the case of "DO NOT graze treated crops", the treated crop can never be grazed during its life cycle, including any crop residue post harvest.

It is the responsibility of the owner of any agricultural produce that has been treated to ensure that all relevant WHPs are complied with.

If animals graze on treated plants before the WHP expires, or if treated plants are cut and fed as stockfeed before the WHP expires, there is a possibility that the animals may contain unacceptable residues. Any agricultural produce derived from the animals (e.g. meat, milk, eggs, and wool) may also contain unacceptable residues.

When a contractor applies an agvet chemical to agricultural produce on behalf of the owner of the produce, it is essential to inform the owner about the application of any relevant WHPs that need to be adhered to.  

### 6.4 Record keeping

It is mandatory to make and retain accurate and detailed records when applying certain crop protection products across Australia. It is good farming practice to keep detailed spray records of all chemical applications.

These records should be made within 24 hours of spraying and be kept for at least two years, depending on state regulations and label requirements.

Details to record include:
- Location of paddock sprayed;
- Crop/situation and weed/pest;
- Application date, including start and finish times;
- Full name of the product, active ingredient and loading and product batch number;
- Product application rate per hectare, water volume, and number of hectares treated; Weather information including wind speed and direction, air temperature, relative humidity and cloud cover during application;
- Nozzle type, spray angle and spray pressure during application;
- Name and address of person applying the product;
- Personal protective equipment used; and
- Any additional information required as directed by the label or permit.  

Additional record details may be required by the state or territory where this product is used.

Record keeping software has also become more intuitive and devices are increasingly being integrated and connected with operations performed on a daily basis. Increased connectivity is allowing the sharing and accumulation of data without the need to use cards, sticks or discs. Records are also becoming more visual, with the GPS capabilities of many devices allowing data to be viewed easily on farm maps.

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An increasing number of record-keeping applications are now available, from simple spray-recording apps through to integrated whole-of-farm management systems that link growers with their consultants and agronomists. Choosing a record-keeping system will depend on many factors;

- whether you need to link with your agronomist
- if you require the system to integrate with your precision agriculture data
- whether you want one system to do everything or if you are happy to run a few smaller apps to achieve a similar outcome.  

### 6.5 Training and legal requirements

In Australia, growers must complete an approved chemical user training course before operating spray rigs, depending on which state you are in, and are required to keep up-to-date records of pesticide use under Australian law. 

Under the resellers Duty of Care, chemicals can only be purchased and collected by an accredited chemical user.

The accreditation required depends on which state or territory you live in, for example:

- NSW - All people involved in supervising, handling or the application of chemicals should have chemical user accreditation (including contractors),
- Qld - Chemical users applying herbicides on properties other than their own, have chemical user accreditation.

To become accredited you will need to do a course delivered by a Registered Training Organisation (RTO). Training and assessment procedures are based on endorsed national competency standards and only conducted by qualified, trained and accredited instructors working through an RTO.  

A number of trainers provide courses in this space. These can be face to face training sessions or on-line options

See the links below for more information on accreditation training courses:

- NSW DPI
- AnSafe
- ChemCert

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GRDC Projects

Project Summaries
As part of a continuous investment cycle each year the Grains Research and Development Corporation (GRDC) invests in several hundred research, development and extension and capacity building projects. To raise awareness of these investments the GRDC has made available summaries of these projects.

These project summaries have been compiled by GRDC’s research partners with the aim of raising awareness of the research activities each project investment.

The GRDC’s project summaries portfolio is dynamic; presenting information on current projects, projects that have concluded and new projects which have commenced. It is updated on a regular basis.

The search function allows project summaries to be searched by keywords, project title, project number, theme or by GRDC region (i.e. Northern, Southern or Western Region).

Where a project has been completed and a final report has been submitted and approved a link to a summary of the project’s final report appears at the top of the page.

The link to Project Summaries is https://grdc.com.au/research/projects

Final Report Summaries
In the interests of raising awareness of GRDC’s investments among growers, advisers and other stakeholders, the GRDC has available final reports summaries of projects.

These reports are written by GRDC research partners and are intended to communicate a useful summary as well as present findings of the research activities from each project investment.

The GRDC’s project portfolio is dynamic with projects concluding on a regular basis.

In the final report summaries there is a search function that allows the summaries to be searched by keywords, project title, project number, theme or GRDC Regions. The advanced options also enables a report to be searched by recently added, most popular, map or just browse by agro-ecological zones.


Online Farm Trials
The Online Farm Trials project brings national grains research data and information directly to the grower, agronomist, researcher and grain industry community through innovative online technology. Online Farm Trials is designed to provide growers with the information they need to improve the productivity and sustainability of their farming enterprises.

Using specifically developed research applications, users are able to search the Online Farm Trials database to find a wide range of individual trial reports, project summary reports and other relevant trial research documents produced and supplied by Online Farm Trials contributors.

The Online Farm Trials website collaborates closely with grower groups, regional farming networks, research organisations and industry to bring a wide range of crop research datasets and literature into a fully accessible and open online digital repository.

Individual trial reports can also be accessed in the trial project information via the Trial Explorer.

The link to the Online Farm Trials is http://www.farmtrials.com.au/
References

Section 2A: Herbicide Group A modes of action


Section 2B: Herbicide Group B modes of action


Section 2C: Herbicide Group C modes of action


### Section 2D: Herbicide Group D modes of action


### Section 2F: Herbicide Group F modes of action


Section 2G: Herbicide Group G modes of action


Section 2H: Herbicide Group H modes of action


Section 2I: Herbicide Group I modes of action


Section 2J: Herbicide Group J modes of action


Section 2K: Herbicide Group K modes of action


Section 2M: Herbicide Group M modes of action


McWhorter CG, Jordan TN, Wills GD (1980) Translocation of 14C-glyphosate in soybeans (Glycine max) and johnson grass (Sorghum halepense). Weed Science 28,113–118.


REFERENCES


**Section 2N: Herbicide Group N modes of action**


**Section 2Q: Herbicide Group Q modes of action**


**Section 2Z: Herbicide Group Z modes of action**


Section 3: Herbicide resistance


International Survey of Herbicide Resistant Weeds, [www.weedscience.org](http://www.weedscience.org)


Section 5: Health and environmental effects


Section 6: Labelling and training


Contacts

To come