

SOIL BEHAVIOUR OF PRE-EMERGENT HERBICIDES IN AUSTRALIAN FARMING SYSTEMS



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FOR AGRONOMIC ADVISERS**

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Introduction

The importance of controlling weeds in broadacre field crops

Weed management is critical for profitable Australian farming systems. Weeds compete aggressively with grain crops for moisture and nutrients and, if left unchecked, can result in significant crop losses.

In addition to losses from competition, Australian growers spend well over \$1 billion¹ per year on herbicides, to which the additional costs of machinery, labour and contractors to apply these herbicides must be added.

The past 30 years has seen a major revolution in broadacre farming with the majority of grain farmers adopting a minimum or zero-tillage system, which has largely reduced or removed the use of cultivation as a tool for weed control. Also, in many areas, there has been a trend towards growers specialising in 'cropping'. This has led to a decline or elimination of livestock from the farming system, further reducing the diversity of weed control options on many properties. The combined effect has been a significant increase in the reliance on herbicides for weed management in Australian farming systems.

This shift in farming system has seen an evolutionary change in weed species in many paddocks, with increasing dominance of surface or shallow-germinating weeds that are suited to a zero-tillage system, where weed seeds are predominantly left undisturbed on the soil surface.

Since the adoption of reduced tillage practices, controlling weeds on the modern farm has largely become the domain of herbicides, both within the crop and in the fallow between crops. Growers have had a range of cost-effective and efficacious herbicides to rely upon, however there has been a heavy reliance on a few individual modes of action, namely Groups 1, 2, 4 and 9 in particular.

While being quite different in their weed control spectrum and the way that they work within the plant, these herbicide groups have a number of similarities that have seen them gain popularity.

- They provide reliable, consistent performance.
- They are frequently 'cheap' relative to other available weed control options.
- They work primarily as foliar-applied post-emergent herbicides.

The cost-effectiveness, reliability and ease of use of these herbicides has encouraged growers to favour post-emergent options, where they can wait and see which weeds emerge before dealing with the problem.

Unfortunately, evolution continues in our cropping systems. This has seen an increase in the importance of weeds that:

- are adapted to the new farming system i.e. surface-germinating and windblown weed seeds; and
- are resistant to the herbicides previously used to control them.

A recent example of adaptation and evolution is evident in barley grass and brome grass. Continual herbicide selection pressure early in the cropping season has selected for individuals that express a high level of seedbank dormancy leading to a high percentage of the population emerging later in the season and escaping early season control. This is driven by the selection of a vernalisation response (cold requirement before germination) which is under the control of a single gene.

Herbicide resistance and species shift are causing many advisers and growers to radically rethink their approach to weed management, including the introduction of more diversity into their weed control programs. Increased use of pre-emergent herbicides is one tool that increases diversity of the weed control program while also reducing weed numbers, which complements the use of tactics such as crop competition, in-crop herbicides and harvest weed seed control. However increased use of pre-emergent herbicides will also increase the selection pressure placed on these herbicides, underscoring the need to introduce non-herbicide-based weed management tactics into the cropping system, to reduce our reliance on herbicides and thereby prolong their useful life.

The value of pre-emergent herbicides

When devising a weed control strategy, pre-emergent herbicides can be a valuable additional tactic to help drive weed numbers down. Used alone, they often do not achieve the objective of driving down weed seedbank numbers as small numbers of weed escapes often occur and provide seedbank replenishment. However, when used as a component amongst a suite of tactics, they can be particularly effective.

Benefits of pre-emergent herbicides include:

- offers an alternate mode of action to many post-emergent options;
- reduced selection pressure on subsequent post-emergent herbicide applications;
- removal of early season weed competitive pressure often protects crop yield better than later applied post-emergent applications, especially in weedy paddocks;
- cost savings, especially in the fallow where multiple knockdown applications may be required;
- reduced time pressure on other spraying operations, both in crop and in fallow;

¹ Manufacture level sales of \$1.26m for 2012/13 as reported in the *Commonwealth of Australia Gazette* No. APVMA 4, Tuesday 25 February 2014, Page 29

- major role in patch eradication where a weed blow-out can be GPS logged and a pre-emergent herbicide applied to manage the patch;
- after a cultivation event, there will always be some weed seed in a position in the soil profile that is ideal for germination—applying a pre-emergent herbicide after the last cultivation can manage these weeds that would otherwise emerge and ultimately return additional seed to the soil; and
- some crops have few post-emergent options (for example, grass weed control in sorghum, or broadleaf weed control in pulses) and hence often rely on pre-emergent herbicides for in-crop weed control.

Common objections to the use of pre-emergent herbicides

Many growers frequently raise objections when pre-emergent herbicides are discussed. Some of the more common objections are outlined below.

“If it doesn’t rain to germinate the weeds then my money is wasted.”

Most pre-emergent herbicides require rain for incorporation and uptake, although some pre-emergent herbicides can remain on a dry surface for considerable time without degradation. Understanding the properties of the chosen herbicide assists decision making on application timing and the incorporation requirements of the molecule. Usually rainfall, or existing soil moisture, is required to germinate weeds, so the correct timing of pre-emergent herbicide application relative to rainfall and weed germination is important to maximise the value of the investment.

“I applied a pre-emergent herbicide a few years ago and it didn’t work. I can’t rely on them.”

Pre-emergent herbicides are not all the same. The properties of each herbicide dictate where it remains in the soil profile, what conditions are required to maximise performance and how quickly it will break down. As pre-emergent herbicides are strongly influenced by soil type, stubble cover, incorporation, temperature and rainfall, it is quite possible that a different result can be achieved between two adjacent paddocks with application only a few weeks apart.

It is generally much easier to monitor the performance of a post-emergent herbicide. The starting weed population is known and the herbicide effects can be seen over the resulting weeks. With commercial pre-emergent herbicide applications, usually the whole paddock is treated so the magnitude of the weed pressure may be underestimated. As a result, it is usually much more difficult to gauge success and impact of a pre-emergent herbicide application, than it is for a post-emergent application. In situations where growers have been dissatisfied with the performance of a pre-emergent herbicide, they are often surprised if a ‘missed strip’ is found, as this demonstrates what the paddock would be like if the pre-emergent herbicide had not been used.

“Pre-emergent herbicides leach and move in the soil and damage off-target vegetation.”

The properties of some pre-emergent herbicides allow the product to be more available in the soil profile and more able to move with the soil water; while some other herbicides are very tightly bound and unlikely to move. Understanding herbicide properties, in particular the solubility and binding, enables the right product to be selected for the situation.

“Using pre-emergent herbicides locks me out of crop rotation options.”

This is probably the most frequent objection by growers when their adviser recommends a pre-emergent herbicide. By nature of their residual properties, most pre-emergent herbicides will have plant-back constraints to some crops.

However, it is extremely unlikely that a grower will ever apply a particular residual herbicide to the entire farm, so the ‘whole farm’ is not being locked out of a flexible crop rotation. In practice, there is usually a percentage of paddocks where the next crop rotation is firmly locked in. In these paddocks, there is the option to select an appropriate residual herbicide with only a low risk of a negative impact on crop rotations.

When dealing with these common objections, the key underlying theme is that it is critical for advisers to have a thorough understanding of the properties of pre-emergent herbicides under consideration, to enable the best choice to be made.

This manual is a reference for Australian grain advisers, covering the factors influencing the performance and breakdown of pre-emergent herbicides.

Factors influencing the activity of pre-emergent herbicides

To understand how pre-emergent herbicides perform, it is important to know the properties of the herbicide, the soil type and how it is broken down in the environment. Availability of a pre-emergent herbicide is an interaction between: the solubility of the herbicide; how tightly it is bound onto soil colloids and organic matter; soil factors such as structure, cation exchange capacity and pH; herbicide volatility; the environment and particularly soil water; and the rate of herbicide applied.

Understanding the importance of each of these pathways will give guidance as to likely performance of the herbicide in question. However, if one of these factors in the equation is extreme, then this single factor can have an overriding influence on the overall balance and can alter what normally happens in the field.

For example, some herbicides are relatively insoluble and tightly bound to soil colloids or organic matter, which suggest that they are unlikely to leach. However, in a situation of a high initial rainfall event occurring onto a dry soil, even a herbicide with these properties may be moved further down the soil profile before it has the opportunity to bind to the soil. This may mean that the herbicide can move out of the zone where it is required for weed control, or into a zone where it can damage the crop.

Figure 1: Interactions, loss and breakdown pathways of soil-applied herbicides.

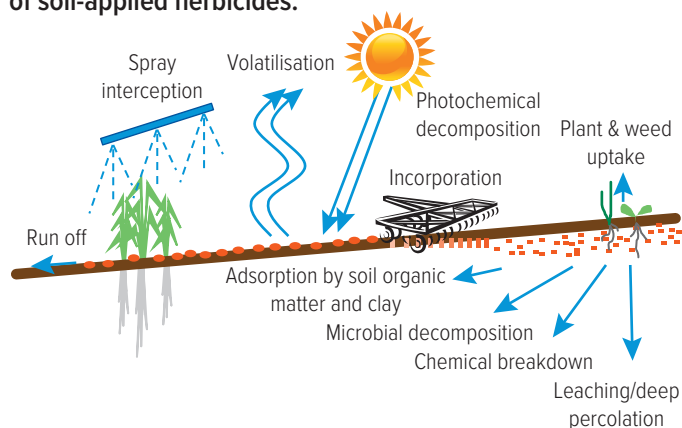
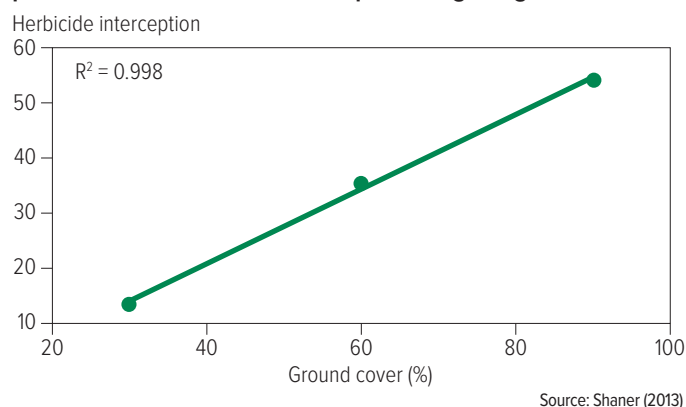


Figure 2: The percentage of herbicide captured by stubble or plant material in relation to the percentage of ground cover.



Interactions prior to incorporation

Stubble and crop interception

Stubble or existing weed cover in a zero or reduced till fallow will intercept some pre-emergent herbicide before it reaches its target – the soil. Likewise, if the pre-emergent herbicide is applied as an in-crop application, a percentage of herbicide will be intercepted by the crop.

The amount of herbicide intercepted will be proportionate to the percentage of ground coverage of the stubble or crop (or weeds if they are already present at application). As shown in Figure 2, while this relationship is linear it should be noted that, for example, 50 per cent ground cover does not result in 50 per cent capture of the herbicide on the above-ground material.

If the pre-emergent herbicide is intercepted by green plant material (for example, existing weeds or crop) the pre-emergent herbicide is likely to enter the green plant material, and therefore not be available in the soil for future residual activity. For some herbicides this may provide additive post-emergent herbicide activity.

In addition to herbicide uptake in green plants, interception by standing material can have other effects.

- For some products, herbicide tied up on the stubble or in the canopy may not be available for soil incorporation and subsequent weed control.
- Interception may lead to an uneven coverage of the soil surface, resulting in areas with insufficient herbicide coverage and potentially weed escapes.

Herbicide intercepted by standing organic material will be subject to a certain level of binding, depending on the herbicide's characteristics (see later section on binding). Some herbicides are tightly bound to crop residues and become lost to the system in terms of weed control, despite subsequent rainfall (for example, trifluralin). Others are loosely bound and relatively soluble and can be returned to the soil by rainfall that 'washes' herbicide off the organic material (for example, chlorsulfuron). To understand the potential level of binding of a herbicide, advisers need to consider its binding coefficient (K_d or K_{oc}) and solubility (see page 11–12). However, even if a herbicide is loosely bound and available to be washed off, it still may be prone to loss due to volatility and photodegradation, before it is incorporated into the soil.

Where high levels of stubble or plant material exist, the level of spray droplet interception can be minimised by adjusting how the herbicide is applied. Some techniques that can increase the proportion of herbicide reaching the soil include:

- wind across the rows during application;
- using rear-facing nozzles where the angle offsets the travel speed, to have droplets moving predominantly downwards through the stubble;

- larger droplets travelling at higher speed
 - select a nozzle and pressure that produces larger droplets
 - narrow fan angles (for example, 65 to 80 degrees) increases droplet speed, while also having droplets travel closer to vertical which reduces stubble interception;
- keep water rates high to maintain coverage when using larger droplets by increasing the number of droplets produced;
- narrower nozzle spacing (25 centimetres vs 50cm);
- slower travel speeds (i.e. <16 kilometres per hour) to reduce horizontal movement (forward trajectory of droplets); and
- minimise boom height, but ensure at least double overlap.

However, consider that the objective of modifying spray application set-up to reduce stubble and weed interception and get a greater percentage of pre-emergent to the soil may often be counter to objectives for weed control if the pre-emergent herbicide is to be mixed with a knockdown herbicide, where application set-up may seek to maximise stubble and weed coverage.

In situations where pre-emergent herbicides are used in-crop, correctly set up directed sprays (layby application) are designed to reduce interception by directing the spray under/away from the crop canopy.

Where herbicides with both pre and post-emergent activity are applied in-crop, the pre-emergent activity is often better when applied during early crop growth stages, as soil coverage may be more even. This is due to less crop interception prior to droplets meeting their target – the soil surface.

For more information on maximising application with pre-emergent herbicides: [youtube.com/embed/s63GYYflzw?start=200&end=473](https://www.youtube.com/embed/s63GYYflzw?start=200&end=473)



Windrow burning at Pithara, WA.

Photo: Evan Collis Photography

Pre-emergent herbicides and windrow burning

With the advent of increasing herbicide resistance, many growers have introduced windrow burning into their integrated weed management strategy. This technique concentrates the previous year's stubble, including the chaff fraction containing the weed seeds, into a narrow band to be burnt in autumn.

If pre-emergent herbicides are used in conjunction with this technique, then consider the following points:

- Applying pre-emergent herbicides over the top of a windrow before it is burnt, will probably result in extremely high levels of herbicide interception and very little on the soil surface under the windrow. So avoid herbicide application prior to burning.
- Always strive for a hot burn within the windrow. This is important to obtain maximum mortality of the weed seeds, but also to maximise the amount of residue converted to ash and minimise the amount left as charcoal. Any unburnt chaff (which will contain high concentrations of weed seeds) can reduce pre-emergent herbicides reaching the soil.
- Herbicides will not generally bind tightly when sprayed onto ash. However, a thick layer of ash may prevent even soil coverage, unless a rainfall event has occurred between the burning and the herbicide application, to disperse the ash.
- Conversely, herbicides will usually bind to charcoal to an even greater extent than they do for green organic matter or stubble. Where charcoal is left after a burning event (or biochar is added to the soil) then it is likely that less herbicide will be available for weed control and herbicide performance may be compromised.

Photodegradation

Photodegradation occurs when the herbicide undergoes a chemical reaction in the presence of sunlight and is then broken down and lost to the weed control system. For most uses of pre-emergent herbicides in Australia, photodegradation is not a significant path of breakdown as standard incorporation practices, such as cultivation, sowing or sufficient rainfall after application, are typically adequate to prevent unacceptable levels of loss. However, when a herbicide is sprayed onto a dry soil surface or dry stubble in summer, with no following rainfall or mechanical incorporation, losses from this pathway will be at their highest, for example using residual herbicides in summer fallow.

Some of the common pre-emergent herbicides that can undergo some level of photodegradation include: the Group 5 herbicides (atrazine, fluometuron, simazine, terbuthylazine and diuron); the Group 2 herbicide sulfosulfuron; the DNA herbicides pendimethalin and trifluralin; the PPO inhibitors oxyfluorfen and saflufenacil; the Group 27 herbicide mesotrione; and the Group 15 herbicide s-metolachlor. Napropamide (Group O) is particularly sensitive to photodegradation, with the label requiring mechanical incorporation within two to four hours post-application.

If these herbicides are applied under warm, dry conditions with no rainfall or mechanical incorporation in the coming weeks, losses can be significant.

Table 1: Potential loss from photodegradation of selected residual herbicides used in Australian broadacre cropping.

2	Sulfonylureas	sulfosulfuron	Half-life 3 days
3	Dinitroanilines (DNAs)	pendimethalin	<5% loss after 30 days from a sandy loam held at 10.2% moisture
		trifluralin	Half-life 44 days
5	Triazines	atrazine	Half-life 45 days on a sandy loam @ 25°C and pH 7.5
		prometryn	Negligible loss after 30 days on sandy loam @ 15–28°C
		simazine	Half-life 21 days on a sandy loam at 25°C
		terbuthylazine	Half-life <40 days
	Ureas	diuron	Not strongly photodegraded, but losses can be significant if diuron remains on the soil surface for several days or weeks
		fluometuron	Half-life 9.7 days on a sandy loam @ 10–36°C
	Triazinones	metribuzin	Insignificant (0.05–0.28% per day)
14	Diphenylethers	oxyfluorfen	Half-life 20–30 days on dry soil
	N-phenyl-imides	saflufenacil	Half-life of 66 days under soil photolysis
15	Chloroacetamides	s-metolachlor	Half-life 8 days on sandy loam @ 15–52°C
27	Triketones	mesotrione	Soil photolysis half-life 15–21 days
0	Acetamides	napropamide	50% loss after 4 days in summer. 30% loss after 8 days in winter

Note: After incorporation has occurred, further losses from photodegradation will be minimal. After incorporation, other degradation pathways will be the primary determination of herbicide loss.

Source: Shaner (2014)

Volatilisation

Some pre-emergent herbicides used in the Australian grains industry are considered volatile. Volatile herbicides transition to a gaseous phase after application if left on the soil surface without incorporation. Some higher volatility herbicides should be incorporated soon after application to avoid significant loss to the atmosphere and therefore maintain their efficacy on weeds.

Loss from volatility is not an 'on/off' switch. For example, if a herbicide label indicates that the product should be 'incorporated within 24 hours' this does not mean that there is no loss up until hour 23 and that it is all gone by the 25th hour. Volatility loss commences as soon as the spray has dried, so with any volatile herbicide it is important to incorporate as soon as possible after application. The time period for incorporation on a label is the time by which the manufacturer has determined that losses may start to become unacceptably high if the product has not been incorporated within this time.

Volatility is highly correlated with temperature, so losses will be highest in summer use patterns or where conditions are still warm. Wind blowing across the surface also increases volatilisation losses, while there will also be different rate of loss depending upon the surface type and moisture level.

Once incorporated into the soil further volatilisation is typically insignificant.

The vapour pressure of a herbicide, usually expressed as millipascals (mPa) at 20°C, provides some indication of the relative volatilisation potential between herbicides. Herbicides with a low vapour pressure (that is, less than 1mPa) are generally referred to as 'non-volatile', while products with a vapour pressure above 1mPa may convert into a gaseous phase and be lost to the atmosphere, unless incorporated post-application. As the vapour pressure increases, so does the urgency to have the herbicide incorporated quickly, to reduce losses.

Table 2 lists some common pre-emergent herbicides in order of volatility to demonstrate the range of vapour pressures.

For more information on volatilisation and incorporation by sowing: [youtube.com/embed/LJNjuMWS57U?start=231&end=516](https://www.youtube.com/embed/LJNjuMWS57U?start=231&end=516)

Table 2: Examples of vapour pressure for selected pre-emergent herbicides and summary of incorporation requirements.

Herbicide	Vapour pressure (mPa @ 20°C) [^]	
Tri-allate (Avadex®)	12	Actives with a vapour pressure of greater than 1mPa are generally considered volatile and are likely to require or benefit from incorporation. Refer to individual product labels for specific situations.
Trifluralin (Treflan®)	9.5	
Cinmethylin (Luximax®)	8.1	
S-metolachlor (Dual®)	3.7	
Pendimethalin (Stomp®)	3.34	
Dimethenamid-P (Outlook®)	2.5	
Bixlozone (Overwatch®)	1.1	
Prosulfocarb (Arcade®)	0.79	Actives with a vapour pressure of less than 1mPa are generally considered low or non-volatile and do not usually require any specific incorporation recommendations after application.
Flumioxazin (Valor®)	0.32	
Terbuthylazine (Terbyne®)	0.152	
Metribuzin (Sencor®)	0.121	
Metazachlor (Butisan®)	0.093	
Propyzamide (Rustler®)	0.058	
Atrazine (Gesaprim®)	0.039	
Napropamide (Devrinol®)	0.02	
Aclonifen (in Mateno® Complete)	0.016	
Imazapic (Flame®)	0.01	
Mesotrione (Callisto®)	5.7×10^{-3}	
Diflufenican (Brodal®)	4.25×10^{-3}	
Fomesafen (Reflex®)	4×10^{-3}	
Carbetamide (Ultro®)	3×10^{-3}	
Pyroxasulfone (Sakura®)	2.4×10^{-3} @ 25°C	
Triasulfuron (Logran®)	2.1×10^{-3}	
Diuron (various)	1.15×10^{-3}	
Simazine (Gesatop®)	8.1×10^{-4}	
Isoxaben (Gallery®)	2×10^{-4}	
Isoxaflutole (Balance®)	3.22×10^{-5}	
Chlorsulfuron (various)	3.07×10^{-6}	
Trifludimoxazin (in Voraxor®)	1.1×10^{-7}	
Saflufenacil (Sharpen®)	4.5×10^{-12}	

[^] University of Hertfordshire, (2006–2023) Accessed on 23 June 2023.

How quickly is trifluralin lost without incorporation?

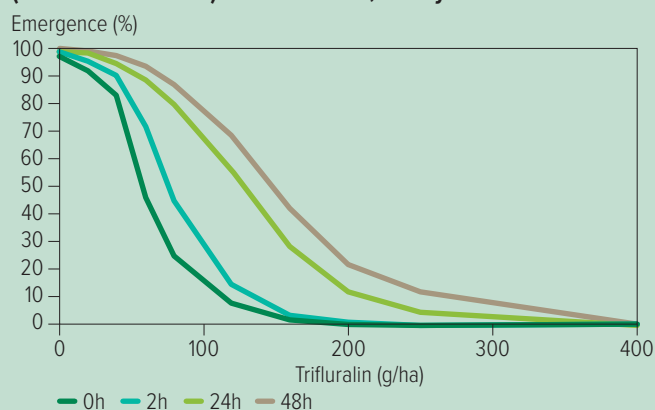
The speed of herbicide loss to volatility depends on many factors, many of which are specific to each application. Factors that affect volatility loss include:

- air temperature (higher temperatures increase the speed of volatilisation);
- moisture (volatility generally increases with higher moisture);
- the type of substrate (for example, soil surface, stubble);
- soil type (volatility will generally be higher on soils with less binding potential);
- wind speed (volatility will generally increase with increasing air flow across the treated surface; and
- the volatility of the compound.

The vapour pressure of a herbicide can be measured under a controlled set of conditions and provides one measure to compare herbicides, that is, the higher the vapour pressure the faster the herbicide will be lost, all other things being equal. The vapour pressure of trifluralin is reported as 9.5mPa @ 20°C, or 13.7mPa @ 25°C, making it potentially one of the more volatile pre-emergent herbicides used in broadacre grain production.

An interesting trial conducted under controlled temperature sought to evaluate the impact of volatility loss on trifluralin on annual ryegrass when incorporation was delayed by up to 48 hours. Pots of sandy, alkaline soil had trifluralin applied at a range of application rates, with incorporation at 0 (incorporated immediately), 2, 24 and 48 hours after application. Annual ryegrass was planted after the last incorporation timing. The pots were then kept indoors to minimise loss from UV light and wind. Herbicide dose response curves were generated.

Figure 3: Effect of time until incorporation and trifluralin application rate on mean emergence of annual ryegrass (of 25 seeds sown) in an alkaline, sandy soil.



Source: Eureka! AgResearch (2015)

As can be seen from Figure 3, delaying incorporation significantly increased the amount of trifluralin required to obtain the same level of control.

ED₅₀ values (estimated dose to achieve 50 per cent control) were established and a percentage loss due to trifluralin volatility was calculated.

Table 3: ED₅₀ and trifluralin loss with time to incorporation on an alkaline, sandy soil.

Incorporation time after herbicide application (hours)	0 hrs	2 hrs	24 hrs	48 hrs
ED ₅₀ (gai/ha)	57	75	136	150
Est. % trifluralin lost	0%	24%	58%	62%

Source: Eureka! AgResearch (2015)

Incorporation

Without incorporation, some herbicides are more predisposed to breakdown and loss from volatilisation and/or photodegradation. Some active ingredients are quite volatile and significant losses from the soil surface can occur if the herbicide is not incorporated within hours or days of application. At the other extreme, other active ingredients have a very low vapour pressure and are not subject to photodegradation, so can remain on the soil surface for days and possibly even weeks without significant loss from these pathways.

Incorporation usually takes one of four forms:

1. Full cut mechanical incorporation

Prior to the advent of reduced tillage, this was the major incorporation method used in Australia and involved a light to moderate mechanical cultivation, usually with harrows or offset discs. This form of incorporation works well for highly volatile products such as trifluralin and tri-allate, provided it is done within hours of the spray application. Historically it was common to see harrows being towed directly behind the boomspray, or operating in the same paddock while spray application was still underway.

2. Incorporation by sowing (also commonly referred to as IBS)

This tactic is used extensively in reduced and zero-till farming systems. A knife point seeder is set up to 'throw' a small amount of treated soil out of the sowing furrow and onto the inter-row to cover the herbicide, which has been previously applied to the soil surface. Typically this will only work with seeders set up to plant on approximately 25 to 30cm row spacing. Careful attention to seeder set-up is required to ensure even inter-row coverage while preventing throw of treated soil into the next furrow.

With some volatile herbicides (for example, trifluralin and tri-allate), the labelled rate for IBS application is often much higher than that used in a full cut incorporation method. A higher application rate used with these herbicides in an IBS system is possible due to:

- limited mixing of the treated soil which means there is greater separation between the herbicide band near the soil surface and the crop seed;
- increased binding to retained stubble;
- much of the herbicide above the crop row is removed and displaced into the inter-row area; and
- incomplete soil coverage of the herbicide which often results in greater volatility losses.

These factors reduce the potential for contact between the herbicide and the emerging crop.

3. Irrigation

If overhead irrigation is available, then this can be used to incorporate some herbicides. The volume of water required will depend upon the soil type, ground cover, solubility of the herbicide and the existing soil moisture. Typically a 5 to 10 millimetre irrigation event is usually satisfactory for herbicides with higher solubility, while 20 to 50mm may be required for herbicides with 'low' solubility. It is important not to over water and risk moving the herbicide down the soil profile before binding has occurred.

Other forms of irrigation such as furrow irrigation are not recommended for herbicide incorporation. This is due to: unevenness of soil wetting between the start and finish of the furrow; too much irrigation water is usually applied; run-off into tail ditches; and the fact that furrow irrigation also wets along a horizontal front. Also, herbicide located on the top of irrigation furrows is only incorporated by capillary action from below (sometimes referred to as 'subbing-up'). This may lead to an inadequate level of herbicide incorporation in these zones.

4. Rainfall

Rainfall is often relied on and used for incorporation, especially in fallow situations. In this case, applications should be made prior to a forecast rainfall event. As forecasts do not always eventuate and rainfall volume can be highly variable, this practice can lead to inconsistent results.

In situations where incorporation is advisable, the objective is to move the herbicide into the top few centimetres of soil where it will be protected from UV degradation and volatilisation, yet still keeping it in the zone required for weed control (which is often close to the soil surface for shallow-germinating weeds, especially in zero-till systems).

Herbicide behaviour in the soil

Once a pre-emergent herbicide is in the soil, an equilibrium is established between how much is bound to clay and organic matter, and is therefore initially unavailable for plant uptake, and how much is dissolved in the soil water and available to the plant. Factors that affect the degree of binding: are the soil type (structure, pH and cation exchange capacity); organic matter in the soil; the solubility of the compound; the amount of available soil moisture; and the inherent binding strength of the molecule.

Position of the herbicide in the soil

The location of targeted weed seeds is an important consideration. In a zero-till environment, most weed seed is likely to be located on or near the soil surface. In a zero-till system, it is most likely that pre-emergent herbicides that bind and stay relatively close to the soil surface in the zone where the weed seeds are germinating will perform adequately.

Conversely, if deeper germinating weeds are the target, then having a herbicide which stays tightly bound to the soil surface may allow weeds to germinate at depth and be able to grow through the herbicide band on the soil surface.

A practical example of this would be where trifluralin is used on annual ryegrass.

In a tilled system, ryegrass seed is spread through the soil surface to the depth of tillage. When trifluralin was applied at or prior to sowing and harrowed in, it was also mixed in this zone. This diluted the trifluralin throughout the surface zone. At the rates that could be used in this use situation, weed control would often be marginal. Crop damage was also a concern, as the trifluralin treated zone was often close to, or just above, the depth of the crop seed.

In modern no-till systems, weed control using trifluralin via 'incorporate by sowing' (IBS) application often results in higher levels of control than in traditional tilled systems with full incorporation. In a no-till system, ryegrass seeds are concentrated on or near the soil surface, as is the herbicide. Higher rates can be applied as the margin for crop selectivity is larger than in a full mechanical incorporation system, due to greater spatial separation between the narrow herbicide band at the soil surface and the deeper cereal seed. Also, the herbicide over the row is displaced into the inter-row at sowing—further enhancing crop selectivity, while also reducing volatilisation loss of the herbicide.

For more information on how zero/minimum till farming influences pre-emergent herbicides: [youtube.com/embed/s63GYyflzw?start=48&end=113](https://www.youtube.com/embed/s63GYyflzw?start=48&end=113)

Soil texture and cation exchange

The type of soil often has a significant bearing on the performance of the pre-emergent herbicide. Soil texture (the ratio of sand, silt and clay) and soil organic matter will have an effect on the binding ability of the herbicide (adsorption). Cation exchange capacity (CEC) is used as a measure of the soils' adsorption sites where binding can occur.

Heavier clay soils and soils with higher organic matter have more binding sites (higher CEC) and can bind more herbicide. Increased binding is likely to result in higher application rates being required to achieve a given level of weed control, as less herbicide is available in the soil water for uptake by germinating weeds. Increased binding also generally results in less leaching.

Conversely, in sandy or low organic matter (lower CEC) soils, there is less binding with more herbicide likely to be available in the soil water. This may lead to increased risk of injury to crops soon after application where there is a lot of freely available herbicide in the soil water, especially for highly soluble herbicides. As a result, many labels recommend a lower application rate in lighter soils. Soil with a CEC of less than 2 can be extremely problematic, with very little binding occurring and therefore much increased herbicide availability to the crop.

Duplex soils with a sandy shallow topsoil over a heavier B horizon can be particularly challenging. Low binding and high availability may apply in the A horizon, but strong binding and therefore persistence of the herbicide may occur in the B horizon. This can lead to high levels of exposure to the crop early after application, with long-lived persistence for some products.

Herbicide properties affecting soil binding and availability

Solubility

Solubility is a measure of how much herbicide can dissolve in water, an important consideration with regard to incorporation by rainfall or irrigation and uptake by the germinating weeds. Solubility is usually quoted in mg/L of water at 20°C.

Herbicides with low water solubility often require larger volumes of rainfall to achieve incorporation and tend to be less available in the soil moisture than more soluble products. Typically, for optimum performance, herbicides with low solubility need good moisture conditions after application and also for the period of desired weed control.

Conversely, herbicides with high solubility are relatively easy to incorporate with limited rainfall, so may be preferred in situations with heavy stubble interaction, for example, stripper front systems, chaff lining or situations where livestock have trampled stubble. They generally have a higher portion of herbicides in the soil moisture phase where they are more freely available to the plant or weed. However, if the herbicide is highly soluble it will have a tendency to move with the soil moisture, and be more likely to leach or cause off-target effects.

For more information on how solubility affects pre-emergent herbicides: [youtube.com/embed/s63GYyflzw?start=478&end=573](https://www.youtube.com/embed/s63GYyflzw?start=478&end=573)

Binding

When a herbicide is incorporated into the soil, a percentage will bind to the soil organic carbon and soil particles.

The degree of binding can be predicted by considering the Soil/Water Adsorption Coefficient (K_d). The K_d value is the ratio of herbicide adsorbed onto the soil in comparison to the amount remaining in the soil water.

It is calculated as follows:

$$K_d = (\text{kg herbicide/kg soil}) / (\text{kg herbicide/L water})$$

As binding is highly influenced by the level of organic matter, the binding coefficient is often normalised to take into account organic carbon levels in different soils and is presented as a K_{oc} value.

The K_{oc} value is calculated by the equation:

$$K_{oc} = K_d / \text{soil organic carbon}$$

The higher the K_{oc} value, the more tightly the herbicide is bound. Herbicides with a low K_{oc} are less tightly bound to the soil and more freely available in the soil water. As a result, they have greater capacity to move with the soil water, especially in sandy soil or soils with low organic matter.

For some molecules the K_{oc} is very sensitive to soil pH, in particular the imidazolinone herbicides which bind tighter at acidic (low) pH.

As soil factors may have a significant bearing on the level of binding, K_{oc} will often be reported as a range (usually with an average across trials), especially where the range is broad.

For some pesticides, binding is reported as the Freundlich soil-water distribution coefficient (K_f), and then also normalised for soil organic carbon to give K_{foc} . For the purpose of understanding herbicide binding, both K_{oc} and K_{foc} are similar.

Figure 4: Pre-emergent herbicide mobility in the soil is primarily influenced by solubility and binding.

Tight binding	Relatively tight binding	Low mobility	Some mobility	Mobile
pendimethalin trifluralin	aclonifen prosulfocarb tri-allate	diflufenican diuron flumioxazin isoxaben napropamide propyzamide trifludimoxazin	atrazine bixlozone cinmethylin pyroxasulfone simazine terbuthylazine	Group 2 Group 4 carbetamide fomesafen mesotrione metazachlor metribuzin s-metolachlor saflufenacil
Well suited to IBS (incorporated by sowing) with knife points and press wheels				Higher potential for crop damage

Table 4: Examples of solubility of selected pre-emergent herbicides.

Herbicide	Solubility (mg/L @ 20°C) [^]	
Diflufenican (Brodal [®])	0.05	Low solubility (0 to 49mg/L @ 20°C) Likely to require moist conditions for incorporation and uptake
Trifluralin (Treflan [®])	0.22	
Pendimethalin (Stomp [®])	0.33	
Flumioxazin (Valor [®])	0.8	
Isoxaben (Gallery [®])	0.9	
Acifluorfen (in Mateno [®] Complete)	1.4	
Trifludimoxazin (in Voraxor [®])	1.8	
Pyroxasulfone (Sakura [®])	3.5	
Tri-allate (Avadex [®])	4	
Simazine (Gesatop [®])	5	
Isoxaflutole (Balance [®])	6	
Terbutylazine (Terbyne [®])	7	
Propyzamide (Rustler [®])	9	
Prosulfocarb (Arcade [®])	13	
Atrazine (Gesaprim [®])	35	
Diuron (various)	36	
Bixlozone (Overwatch [®])	40	
Fomesafen (Reflex [®])	50	Moderate solubility (50 to 500mg/L @ 20°C)
Cinmethylin (Luximax [®])	58	
Napropamide (Devrino [®])	74	
Metazachlor (Butisan [®])	450	
S-metolachlor (Dual [®])	480	
Picloram (Tordon [®])	488	
Triasulfuron (Logran [®])	815	High solubility (>501mg/L @ 20°C)
Metribuzin (Sencor [®])	1100 [#]	
Dimethenamid-P (Outlook [®])	1499	
Mesotrione (Callisto [®])	1500	
Saflufenacil (Sharpen [®])	2100	
Imazapic (Flame [®])	2230	
Carbetamide (Ultro [®])	3270	
Clopyralid (Lontrel [®])	7850	
Chlorsulfuron (various)	12,500	

[^] University of Hertfordshire (2006–2023). Accessed on 26 June 2023.

[#] Shaner (2014).

Table 5: Examples of average adsorption coefficients for selected pre-emergent herbicides.

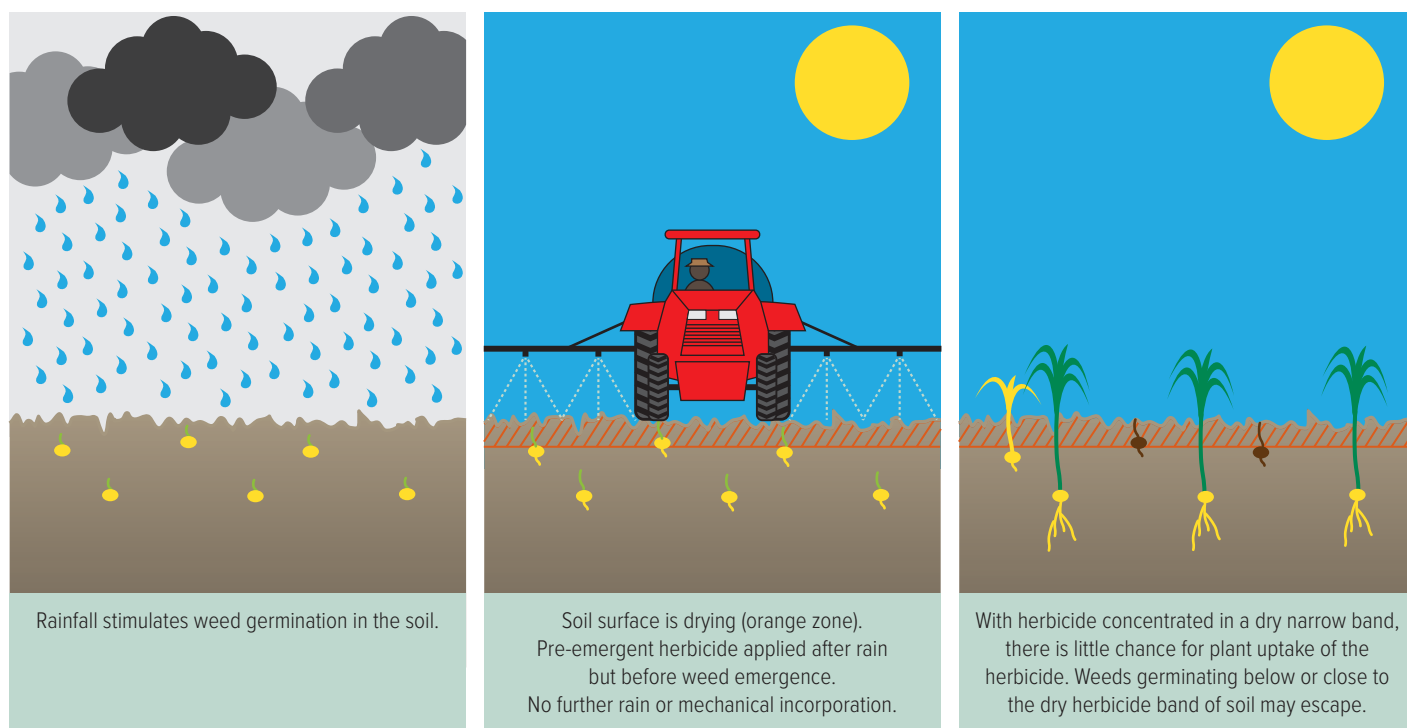
Herbicide	Average K_{oc} value [^] (K_{loc} where stated)		
Pendimethalin (Stomp®)	17,491	>5000 Non-mobile	Likely to bind tightly to soil and organic matter
Trifluralin (Treflan®)	15,800		
Aclonifen (in Mateno® Complete)	7126 (K_{loc})		
Tri-allate (Avadex®)	3034	500 to 5000 Slightly mobile	
Diflufenican (Brodal®)	1622–2369 [#]		
Prosulfocarb (Arcade®)	1693 (K_{loc})		
Isoxaben (Gallery®)	909		
Flumioxazin (Valor®)	889		
Propyzamide (Rustler®)	840		
Napropamide (Devrinol®)	839		
Diuron (various)	680		
Trifludimoxazin (in Voraxor®)	436 (K_{loc})		
Bixlozone (Overwatch®)	315–541 (K_{loc})		
Cinmethylin (Luximax®)	318 (K_{loc})	75 to 500 Moderately mobile	More likely to move with soil water
Terbuthylazine (Terbyne®)	231 (K_{loc})		
Dimethenamid-P (Outlook®)	227 (K_{loc})		
Pyroxasulfone (Sakura®)	223		
S-metolachlor (Dual®)	200 (K_{loc})		
Isoxaflutole (Balance®)	145		
Imazapic (Flame®)	137		
Simazine (Gesatop®)	130		
Mesotrione (Callisto®)	122		
Atrazine (Gesaprim®)	100		
Carbetamide (Ultro®)	89		
Triasulfuron (Logran®)	60		
Metazachlor (Butisan®)	54		
Fomesafen (Reflex®)	50		
Metribuzin (Sencor®)	48 (K_{loc})		
Chlorsulfuron (various)	36 (K_{loc})	20 to 75 Mobile	
Saflufenacil (Sharpen®)	9–55 ^{@5}		
Picloram (Tordon®)	13		
Clopyralid (Lontrel®)	5		
		0 to 20 Very mobile	

[^] University of Hertfordshire (2006–2023). Accessed on 26 June 2023.

[#] Shaner, D. (2014).

^{@5} APVMA (2012).

Figure 5: Dry topsoil with inadequate soil water to allow herbicide uptake by emerging weeds – the perfect storm for weed escapes.



To understand how this affects interaction in the soil, compare the solubility (Table 4) and average K_{oc} values (Table 5) for the commonly used Group 5 herbicides atrazine and diuron. Both atrazine and diuron have similar (and low) solubility. However the adsorption coefficient for diuron is significantly higher, indicating that it will bind tighter to the soil and organic matter at the soil surface, and hence it is effective on many small-seeded, surface-germinating weeds. Conversely, atrazine is more loosely bound to the soil and will move further down the profile with the wetting front after each significant rainfall event. Therefore, what is often observed is that atrazine can provide reasonable levels of control of surface-germinating weeds if there is just enough rainfall to incorporate the herbicide, but not too much to move it deeper in the profile. With additional rainfall, atrazine will move further down the soil profile, often into a 5 to 10cm zone where many larger seeded broadleaf weeds germinate. Atrazine frequently performs better against these larger seeded/deeper germinating targets than diuron, which is more tightly bound and more likely to remain in the top 0 to 2cm zone.

For more information on how binding affects pre-emergent herbicides: youtube.com/embed/s63GYyflzw?start=602&end=779

Soil moisture

Free soil moisture is critical to the performance of most pre-emergent herbicides. With low available soil water, pre-emergent herbicides that rely on root uptake will be less available.

For herbicides with low solubility, lower levels of herbicide will be dissolved in the available soil water than for herbicides with higher solubility. In situations of high available soil moisture, weeds take up adequate soil moisture containing herbicide, even where herbicide solubility is low. However, where soil water is low there may be insufficient herbicide entering the plant with these low-solubility herbicides. This is why many low-solubility, pre-

emergent herbicides may fail to provide good weed control under dry or 'lower soil water' conditions. To maximise performance of low-solubility herbicides, good soil moisture is required, both for incorporation and for the desired period of weed control.

Once in the soil, the herbicide establishes an equilibrium between the amount available in the soil water and that binding onto soil colloids and organic matter. After a herbicide is incorporated, it typically takes several days for this equilibrium to establish. Most new herbicide labels will generally have a constraint to the effect of 'Do not irrigate' or 'Do not apply if run-off rainfall is expected' within two or three days after application. This is partially to allow time for soil binding to take place and the equilibrium to be established.

Once an equilibrium is established, it is an active process with herbicide constantly sorbing or desorbing from binding sites in ratios defined by its binding coefficient values. As some of the 'available' herbicide is lost from the soil water phase—either through plant uptake, leaching or degradation—some of the herbicide that was bound will be released back into the soil water so as to maintain the equilibrium as determined by the product chemistry (the K_{oc} value).

A worst-case scenario for pre-emergent herbicide efficacy is depicted in (Figure 5). The solution is generally to apply the pre-emergent herbicide before a rain front, rather than immediately after one.

Using pre-emergent herbicides after soil amelioration

Deep ripping or spading is designed to break up and mix the upper soil layers. Pay particular attention to furrow opening and closing when using pre-emergent herbicides following soil amelioration. These practices may increase the risk of seeding furrow collapse, with herbicide-treated soil falling back on top of seed.

Tillage practices may also distribute some of the weed seeds deeper throughout the soil profile. IBS application with non-mobile herbicides is designed to be used in a zero-till farming system, with the herbicide positioned close to the soil surface where the weed seeds will be located.

Following more aggressive tillage and therefore more mixing of weed seeds in the soil, weed seeds that germinate from deeper in the profile may not come into contact with sufficient concentration of herbicide and this can lead to poor weed control.

Full inversion tillage, using mouldboard or one-way ploughs, is designed to place all the weed seeds at a depth from where they will not be able to emerge. Provided this is achieved, it may reduce the need for pre-emergent herbicides in the year following inversion tillage. However, if pre-emergent herbicides are used following inversion tillage they can often behave differently. There will be very low levels of organic matter and soil microbes at the soil surface following inversion tillage, which is likely to result in much greater herbicide availability and hence a greater risk of crop injury, especially on lighter soils. Conversely, if soil brought to the surface has a significantly higher clay content then it can be possible that more herbicide could be bound to this 'heavier' soil.

Breakdown

Once in the soil, herbicide breakdown typically occurs via microbial degradation or chemical reactions such as hydrolysis.

For many herbicides, microbial degradation is the primary path of degradation. Conditions that encourage soil microbes (warm soils, good soil moisture, adequate oxygen, organic matter, nutrients and neutral pH) will typically see faster degradation and shorter persistence of the herbicide.

Rainfall in summer, when conditions are warm, will lead to much higher microbial populations than rainfall in the colder months. Extended dry periods which do not support the sustained activity of microbial populations can substantially increase the persistence of these herbicides. If the top 10 to 15cm of soil is dry, then little herbicide degradation is occurring, regardless of how many months have passed.

Many labels will have a plant-back period specifying the number of months and a rainfall requirement from application until susceptible crops can be sown. Rather than considering the rainfall in total, it is better to think in terms of number of weeks of moist topsoil. A single rainfall event with months of dry topsoil is less effective at sustaining microbial populations compared to the same rainfall occurring as a number of events that keep the topsoil wet for longer. Some more recent label plant-back statements now indicate the amount of rainfall required to wet the soil adequately to commence microbial degradation, and may include a warning that the number of months for plant-back only starts from after this initial rainfall is received. Other labels may also have statements indicating that, for example, 'at least half of the stated rainfall amount needs to fall within the first half of the plant-back period'. While directions for plant-back periods and rainfall requirements are product specific, these principles of the importance of an initial soil wetting and having the soil wet for longer periods early in the plant-back period are useful for all residual herbicides.

A mobile herbicide (high solubility/low binding) that is only degraded by microbes may persist for long periods deeper in the soil profile where there is little microbial activity. Good examples of this are the Group 4 pyridines (for example, picloram, clopyralid) and the Group 2 imidazolines and sulfonyleureas. Should these mobile herbicides move to depth and into a zone of low microbial activity, they are more likely to carry over to following seasons and affect rotational crops when the crops' roots get down to access the herbicide at depth.

Enhanced microbial degradation

For some residual herbicides that are broken down by microbes, accelerated degradation has been reported where the herbicide has been applied frequently to the same soil. Atrazine (Group 5), propyzamide (Group 3) and carbetamide (Group 23) are the herbicides most cited in Australian literature, however there is evidence of this occurring with many residual herbicides if they are used frequently (Arbeli & Fuentes, 2007).

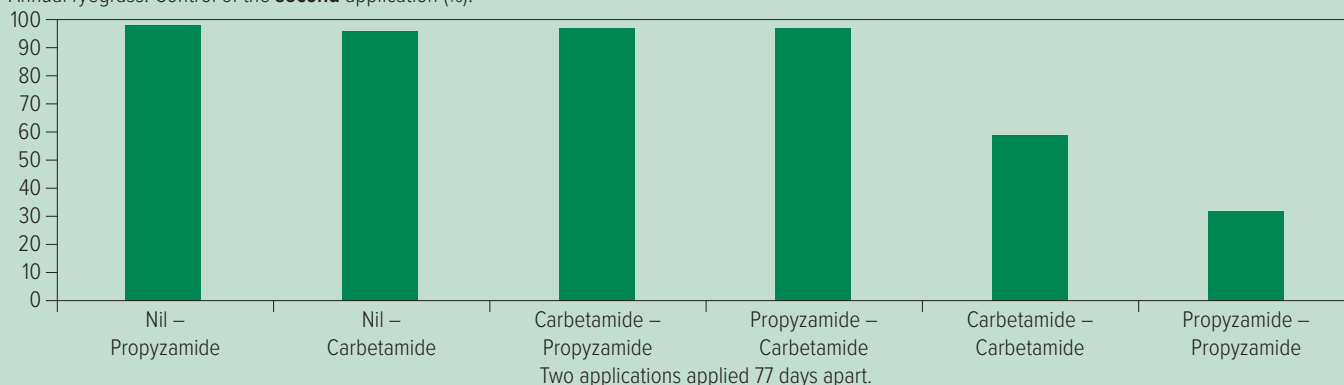
For example, a 1994 trial conducted at Naracoorte, South Australia (Figure 6) showed that control of ryegrass declined significantly from a second application of the same herbicide in the same season.

A number of studies demonstrating enhanced microbial degradation of atrazine under a range of agricultural situations have been published Popov et al. (2005); Mandelbaum et al. (2008).

Should accelerated degradation occur in the field, the length of residual weed control will be reduced. This may also have an impact on plant-backs to rotation crops.

Figure 6: Effect of sequential applications of propyzamide or carbetamide on ryegrass, Naracoorte, SA.

Annual ryegrass. Control of the **second** application (%).



Source: Hole and Powles (1997)

In deep, free-draining soils, these mobile herbicides may be moved deeper in the profile following each major rainfall or irrigation event, potentially moving out of the crop root zone of the following crop. However, problems often arise with mobile herbicides where there is a soil change, pH change or some other structural limitation that causes the herbicide to concentrate at depth and prevents further leaching.

Soil pH generally does not have a large impact on the persistence of most herbicides where the primary breakdown pathway is via microbial degradation. However, there are exceptions. One exception is the imidazolinones, where the strength of binding is strongly influenced by soil pH. The bioavailability of imidazolinones is increased in higher pH (alkaline) soils and this higher availability in solution also makes imidazolinone herbicides more available for microbial degradation. In low pH (acidic) soils, binding of imidazolinones increases, thus reducing bioavailability to plants and weeds and also to the microbes required for breakdown, resulting in increased persistence at acidic pH.

For some herbicides that breakdown via hydrolysis (a chemical reaction), the speed of breakdown is influenced by temperature, moisture and is often highly influenced by pH. The Group 5 sub-group of triazines and the Group 2 sub-group of sulfonylureas typically undergo chemical hydrolysis in neutral or acid soils. However, the speed of this reaction decreases (or ceases) as pH increases. Under high pH (alkaline conditions), breakdown then occurs via the slower process of microbial degradation, so they persist much longer in alkaline soils.

Particular problems are often seen with triazines and sulfonylureas in duplex soils that have an alkaline and impermeable subsoil. In these soils, herbicide that is moved deeper in the profile encounters the alkaline subsoil, where hydrolysis is slow or does not occur. At this depth there is generally minimal microbial activity, so these herbicides can persist for multiple years in these situations.

As a herbicide is lost to the system (broken down by microbes or hydrolysis, taken up by plants or leached down the profile), the equilibrium between the herbicide in the soil and the water phase will remain in the same ratio (as determined by the K_d value of the herbicide). Typically, this means that the balance of sorption/desorption will see some of the herbicide gradually released back into the soil water (desorption) to keep the ratio (sorbed/desorbed) constant.

In this way, residual herbicides provide extended periods of weed control. After the herbicide has been incorporated into the soil, a portion of the herbicide binds to soil and organic matter and some is freely available in the soil water. Herbicide is lost from the soil water phase (degradation, leaching, taken up by plants) and this is then 'replenished' over time from herbicide previously bound to the soil and organic matter that is released back into soil solution.

Persistence

How long a herbicide remains in the soil can be highly variable and depends upon the soil type (binding), temperature, water, organic matter, speed and type of breakdown, and application rate.

The rate of herbicide persistence is usually reported as a DT_{50} value. The DT_{50} value is a half-life, or the days of time that it takes for 50 per cent of the herbicide in the soil to break down. The rate of breakdown varies between different soils and environmental conditions, so the DT_{50} is often reported as a range of values, or an average, or both. While it is common to compare 'average' values to understand differences between herbicides for length of weed control, it can often be the maximum values that may be of more interest for plant-back considerations, especially under climatic conditions that do not favour degradation, for example, dry summers, or soils with low microbiological activity.

In the example following (Figure 7), a moderately persistent theoretical Herbicide A (green line) has a DT_{50} value of 60 days. As can be seen from the graph, if 100 units are applied then after 60 days, 50 units will be remaining. After a further 60 days, 25 units remain. Note that in any biological system, such as a paddock, there will be periods of time where breakdown is faster or slower than the 'average' line depicted in the figure, which will be dependent on environmental factors at that time (particularly soil type, temperature and soil moisture). If it requires 80 units of the herbicide to effectively control the target weed (orange line) it can be seen that Herbicide A will provide approximately 20 days of residual control before there is insufficient herbicide remaining to provide ongoing control.

Molecules with a DT_{50} under 30 days are often classified in herbicide literature as 'non-persistent' as they tend to break down relatively quickly. However, these herbicides classified as 'non-persistent' (DT_{50} less than 30) can still be useful pre-emergent herbicides if applied at a high enough rate to allow them to provide the desired length of residual control.

The graph following (Figure 8) includes an example of theoretical Herbicide B – a 'non-persistent' herbicide that has a DT_{50} of 15 days. Should Herbicide B also require 80 units to control the weed, then it is also possible to obtain the same length of effective residual control by applying a higher starting dose (light green line). A number of pre-emergent herbicides used in the Australian grains industry achieve their stated level of residual control by utilising this concept of high application rates to counter the rapid breakdown.

Figure 7: Persistence over time of a moderately persistent herbicide (DT_{50} = 60 days).

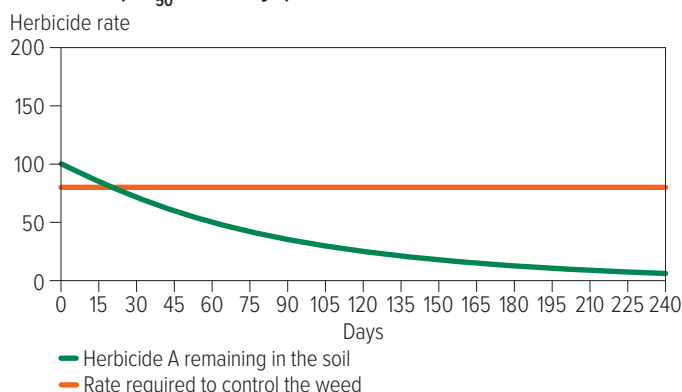


Figure 8: Comparison of a short (DT_{50} = 15 days) and a moderately persistent herbicide (DT_{50} = 60 days) over time.

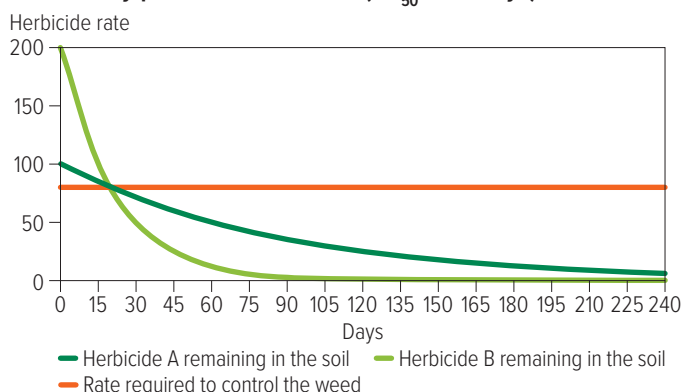


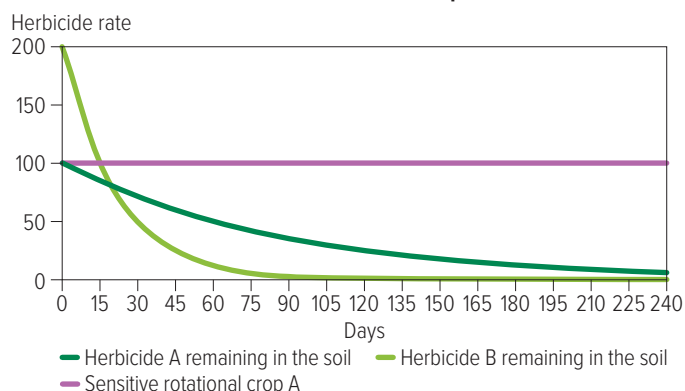
Table 6: Examples of average DT₅₀ values for selected pre-emergent herbicides.

Herbicide (example)	Average (range) DT ₅₀ value [^]		
Mesotrione (Callisto [®])	5 (3–7)	DT ₅₀ 0 to 30 Non-persistent	Unlikely to have plant-back constraints the following year
Metazachlor (Butisan [®])	7 (3–21)		
Carbetamide (Ultro [®])	8 (4–29)		
Prosulfocarb (Arcade [®])	10 (7–13)		
Trifludimoxazin (in Voraxor [®])	14 (7–42)		
Dimethenamid-P (Outlook [®])	16 (10–20)		
Flumioxazin (Terrain [®])	18 (16–20)		
Metribuzin (Sencor [®])	19 (14–28 [#])		
Saflufenacil (Sharpen [®])	20 (7–35)		
Pyroxasulfone (Sakura [®])	22 (16–26)		
Terbuthylazine (Terbyne [®])	22 (16–149)		
Cinmethylin (Luximax [®])	22 (2–208)		
S-metolachlor (Dual [®])	23 (4–56)		
Chlorsulfuron (various)	36 (11–185)	DT ₅₀ 30 to 100 Moderate	Plant-back periods will depend on the sensitivity of the following crop
Triasulfuron (Logran [®])	39 (16–92)		
Clopyralid (Lontrel [®])	8 (2–14) EU 40 (12–70) [#] USA		
Picloram (Tordon [®])	34 (20–49) EU 90 (20–300) [#] USA		
Tri-allate (Avadex [®])	46 (8–205)		
Propyzamide (Rustler [®])	51 (14–271)		
Atrazine (Gesaprim [®])	60 [#] (6–108)		
Aapropamide (Devrinol [®])	72 (31–127)		
Acclonifen (in Mateno [®] Complete)	80 (13–195)		
Fomesafen (Reflex [®])	86 (59–112)		
Simazine (Gesatop [®])	90 (27–102)		
Bixlozone (Overwatch [®])	99 (11–245)		
Pendimethalin (Stomp [®])	100 (40–187)		
Isoxaben (Gallery [®])	123 (66–309)	DT ₅₀ >100 Persistent	Plant-back constraints will occur. Long re-cropping intervals will exist to sensitive crops
Trifluralin (Treflan [®])	170 (35–375)		
Diuron (various)	229 (54–792)		
Imazapic (Flame [®])	232 (31–410)		
Diflufenican (Brodal [®])	(105–210) [#]		

[^] University of Hertfordshire (2006–2023). Accessed on 26 June 2023.

[#] Shaner (2014).

Figure 9: Hypothetical comparison of a short ($DT_{50} = 15$ days) and a moderately persistent herbicide ($DT_{50} = 60$ days) over time relative to a sensitive rotational crop.



Note: These hypothetical examples demonstrate the principle of how application rate, speed of herbicide breakdown and crop/weed sensitivity affects the length of observable symptoms. In practice, different soil types and environmental conditions will vary the speed of breakdown for any herbicide. It is also probable that different species will have different tolerances to each herbicide, unlike the simplified example above.

Any additional stress on germinating weeds or rotational crops will also affect the tolerance of the species to remaining levels of herbicide residue in the soil.

Herbicide manufacturers undertake extensive testing of rotational crops under a range of different environmental conditions and soil types when developing rotational crop recommendations. Always follow the advice on product labels and other supplementary information provided by the manufacturer.

Rotational crop constraints (plant-backs)

By definition, all pre-emergent herbicides, even those classified as non-persistent, usually have some level of plant-back constraint to susceptible crops.

Products that rely on microbial breakdown for degradation require an environment where soil organisms are active for prolonged periods of time. As a biological process, it takes time with adequate soil moisture and temperature for a microbial population to build – a process that is unlikely to occur under dry soil conditions. Often, the amount of total rainfall is less important to microbial breakdown than how long the topsoil, which contains most of the microbes, is moist for.

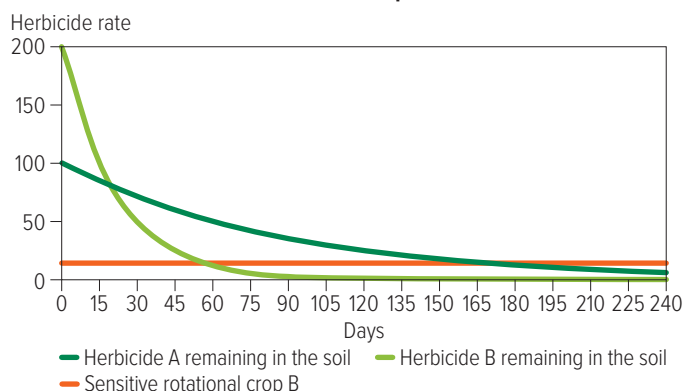
NSW DPI publications *Weed Control in Summer Crops* and *Weed Control in Winter Crops* provide detailed tables of plant-back periods for most pre-emergent herbicides used in grains production in Australia. These tables are relevant to NSW soils and may be different for some products in different states.

ALWAYS check and follow the rotational crop advice on the product label.

Using the example shown in Figure 8, where the use patterns of Herbicide A and Herbicide B were both established to provide a similar length of residual control of the target weed (approximately 20 days), the safe plant-back period to a susceptible rotation crop can vary significantly.

In Figure 9, theoretical rotational crop A can tolerate 100 units of either herbicide (purple line). Therefore, as this rate is the starting application rate of Herbicide A, there is effectively no plant-back limitation for this crop at this application rate of Herbicide A, despite Herbicide A being a moderately persistent product. However, in this example it can be seen that there would be a short, two to three week plant-back to Herbicide B, due to the higher initial application rate, despite Herbicide B being the less persistent product.

Figure 10: Comparison of a short ($DT_{50} = 15$ days) and a moderately persistent herbicide ($DT_{50} = 60$ days) over time relative to a sensitive rotational crop.



However, for these same two theoretical herbicides used in the figures above, a different outcome may be observed if the rotational crop is highly sensitive. In Figure 10, sensitive rotational crop B (orange line) can only tolerate 15 units of either herbicide. This example would indicate that rotational crop B could only be sown approximately 60 days after application of the relatively non-persistent Herbicide B.

However, if the sensitive rotational crop B is to be grown after application of Herbicide A, then a plant-back of approximately 170 days would be required, in this example.

Product labels are designed to cater for typical situations and hence should be followed. However, they may not cover all situations and extremes. In borderline situations, the following strategies may provide additional data on which to assess or reduce risk:

- Soil testing may be possible from a laboratory specialising in herbicide residue testing. This can be time consuming, expensive, and testing may not be available for all herbicides. Sampling depth will also be important. For more mobile herbicides it may be important to check levels at different depths in the profile. Test results will only reveal the quantity of herbicide remaining in the soil as measured by the protocol used by that laboratory. If levels of herbicide are detected, then this will require interpretation to understand if this level will prevent establishment or healthy growth of the desired crop. Data to help interpret test results is limited and often hard to find. For highly active herbicides it could be possible that the laboratory testing protocol may not be sensitive enough to detect quantities that will still damage some rotational crops.
- A simple bioassay can be conducted whereby seeds of the desired crop are sown into the field a few weeks prior to the desired sowing date and establishment is observed to understand the likely level of crop injury. This can give a quick indication as to likelihood of any residues affecting emergence. However care must be taken, especially with

herbicides that are more mobile and may have moved down the soil profile. In this situation adequate degradation may have been achieved in the topsoil where there are higher microbial populations and germination may be unaffected; however severe damage or plant death could still result when the roots of the new crop extend into the residual herbicide layer further down the profile. Also, some herbicides at sublethal doses may not greatly affect emergence, but may significantly reduce biomass after emergence. As such, emergence tests can provide false confidence.

- Aggressive cultivation prior to sowing of a sensitive crop is recommended on the label of some herbicides, typically those that are tightly bound to the soil surface. This may dilute the remaining herbicide throughout the soil profile, allowing improved crop establishment – however this is a risky process to rely on, and is often not compatible with reduced tillage farming systems.
- Switch to a crop variety or crop type that is tolerant to the expected herbicide residue.
- Avoid applications at sowing or early post-emergence from the same herbicide mode of action group that was used in the preceding crop or fallow, as this may 'top up' soil residues.
- Use good agronomy to promote early crop health and vigour and avoid using any practice that might add an additional plant stress to the crop.

How are herbicides taken up by germinating seedlings?

There are two broad pathways for herbicide uptake within the germinating weed seedling. Commonly both pathways are likely to be involved, however typically the chemical properties of the herbicide will dictate which pathway is likely to be the most important for that herbicide.

Solubility in water, volatility in the soil, and binding to soil and organic matter are important factors that will influence uptake. These concepts have been previously discussed in relation to herbicide availability in the soil.

In addition, it is also important to understand the octanol/water partitioning coefficient of the herbicide, which is typically reported as $\log K_{ow}$ or $\log P$ (depending on the reference source cited) (Table 7). $\log K_{ow}$ is calculated by measuring the concentration of herbicide when in octanol, divided by the concentration when in water.

Herbicides with a positive $\log K_{ow}$ value are considered lipophilic and will find it easier to penetrate seed coats and the cuticles around root and coleoptile cells. Lipophilic herbicides have a greater tendency to enter the seed, root or coleoptile node via direct diffusion across the cuticle. The more lipophilic they are, the easier this process will be.

Herbicides with a negative $\log K_{ow}$ value are hydrophilic and will be much more available in the soil water (especially as they often tend to be soluble) and therefore they tend to mainly be taken up by the roots when dissolved in soil moisture.

A summary of uptake pathways

Root uptake, herbicide dissolved in the soil water

Herbicide entry by this pathway will be maximised when a herbicide is neutral to hydrophilic (negative $\log K_{ow}$); has low binding (low K_{oc}) and has high solubility. As an example, most Group 2 herbicides meet these characteristics. Root uptake when dissolved in the soil water is a very efficient uptake mechanism for herbicides with these properties, and therefore becomes the dominant pathway for uptake.

Other herbicides that do not have the 'ideal' chemical properties for this pathway are likely to also use this pathway for uptake, however it will not be as efficient. In particular, herbicides with low solubility may be able to use this pathway when soil moisture is adequate but may deliver sub-optimal uptake as the soil in the germinating zone dries.

Direct diffusion across the cell walls of roots or coleoptile node

Herbicides that are more lipophilic (higher $\log K_{ow}$) will see more herbicide entering the cells via diffusion across the cell wall, compared to hydrophilic herbicides which will have relatively poor uptake via this pathway.

However, for this to occur, the herbicide needs to be in direct contact with the root or coleoptile node cells. This can be achieved by either having available herbicide in the soil water phase (with the amount being a function of the herbicide solubility and K_{oc}), or for a herbicide with some volatility (for example, trifluralin) this may be via herbicide available in the air spaces within the soil.

It may be possible to get some direct diffusion across the seed coat where weed seeds are on the soil surface and a strongly lipophilic herbicide is directly sprayed onto the seed. However, rates required for useful levels of control via this approach are generally not practical in most situations.

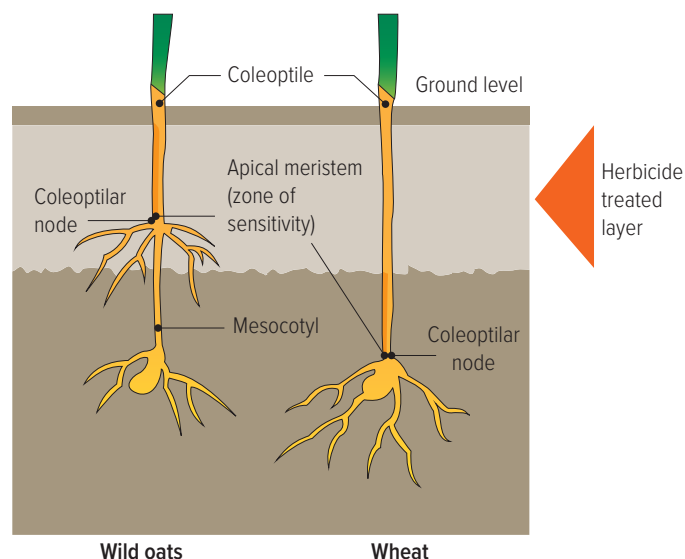
The soil position of the germinating weed seed is important. In zero-till farming systems, most weed seeds will be germinating on or near the soil surface. In this situation, the cells sensitive for diffusion (emerging roots and coleoptile node) will generally be within the area of treated soil and hence reliable control can be achieved.

However, where weed seeds are germinating at depth (often following cultivation which moves some weed seed deeper in the soil profile) it is possible that the important seedling uptake zones may remain below the herbicide, especially for herbicides with low soil mobility (for example, low solubility and high K_{oc}) which is often common for 'lipophilic' herbicides.

Figure 11 highlights the important areas for herbicide uptake – the roots and the coleoptile node.

The role of the coleoptile is largely to protect the emerging shoot as it moves through the soil. The coleoptile is typically less sensitive to herbicide uptake. When referring to herbicide uptake, a commonly used term 'shoot uptake' is somewhat of a misnomer, in that little herbicide typically enters through the shoot.

Figure 11: Different growth patterns in wild oats and wheat contribute to selectivity.



Source: Adapted from Hall (1999)

Table 7: Octanol/water partitioning coefficient for selected pre-emergent herbicides.

Herbicide (example)	Log K_{ow} (or Log P)	
Trifluralin (Treflan®)	5.27	Lipophilic herbicides with a high Log K_{ow} value are more likely to enter the germinating seedling via diffusion
Pendimethalin (Stomp®)	5.4	
Cinmethylin (Luximax®)	4.5	
Prosulfocarb (Arcade®)	4.48	
Aclonifen (in Mateno® Complete)	4.37	
Diflufenican (Brodal®)	4.2	
Tri-allate (Avadex®)	4.06	
Isoxaben (Gallery®)	3.94	
Terbuthylazine (Terbyne®)	3.4	
Trifludimoxazin (in Voraxor®)	3.33	
Bixlozone (Overwatch®)	3.3	
Propyzamide (Rustler®)	3.27	
S-metolachlor (Dual®)	3.05	
Diuron (various)	2.87	
Atrazine (Gesaprim®)	2.7	
Saflufenacil (Sharpen®)	2.6	
Flumioxazin (Valor®)	2.55	
Metazachlor (Butisan®)	2.49	
Pyroxasulfone (Sakura®)	2.39	
Simazine (Gesatop®)	2.3	
Dimethenamid-P (Outlook®)	1.89	Hydrophilic herbicides with a low Log K_{ow} value are more likely to enter the germinating seedling via uptake dissolved in the soil water
Carbetamide (Ultro®)	1.78	
Metribuzin (Sencor®)	1.75	
Imazapic (Flame®)	0.39	
Mesotrione (Callisto®)	0.11	
Chlorsulfuron (various)	-0.99	
Triasulfuron (Logran®)	-0.59	
Fomesafen (Reflex®)	-1.2	
Picloram (Tordon®)	-1.92	
Clopyralid (Lontrel®)	-2.63	

^ University of Hertfordshire (2006–2023). Accessed on 26 June 2023.

However, the coleoptile node is a very important area for soil-active herbicide uptake. As can be seen (left-hand example in Figure 11), some species may germinate from depth and keep their primary roots below the herbicide zone, however control may still be achieved as the mesocotyl elongates and pushes the coleoptile node into the herbicide's zone and herbicide enters through the coleoptile node.

Conversely, some species keep the coleoptile node very close to the seed (right-hand example in Figure 11). If the herbicide has low mobility and stays near the soil surface and the weed seed can keep the roots and coleoptile node below the herbicide band, then the seedling germinating from depth may emerge through the herbicide-treated zone without adverse herbicide uptake through the shoot.

While this is important for weed control, it is also important for cereal crop safety. Wheat and barley keep the coleoptile node close to the seed. Planting depth that keeps the wheat or barley seed below the herbicide band is important for crop safety, especially when using many of the 'grass-killing' herbicides that are quite toxic to cereals. Oats, sorghum and maize undergo mesocotyl elongation that pushes the coleoptile node towards the soil surface, so often there is less crop safety in these crops.

While exceptions exist, lipophilic herbicides tend to also have low solubility and high affinity for binding. This can mean that only low levels of herbicide are available in the soil water phase which can limit how much is available for diffusion, especially under 'dry' soil conditions.

If the herbicide is 'volatile' in the soil then there may be more ability for the herbicide to diffuse through the air spaces. The result being that sometimes herbicides which are more 'volatile' may give an increased level of control in drier soils.

Trifluralin is often cited as a 'volatile' herbicide that may have somewhat increased control under drier conditions. While this is somewhat correct, it should be stated that all herbicides are likely to deliver poor results in dry conditions, trifluralin included. The process of volatilisation requires some level of soil moisture, so will still typically fail where the soil is too dry.

Due to the volatile nature of trifluralin, there will be some herbicide in a vapour phase in the air spaces within the soil. As trifluralin vapour is formed it will start to diffuse towards air spaces with lower trifluralin concentration. However, as indicated by the K_{oc} value, trifluralin also has a strong binding affinity to organic matter and soil. Therefore, as the trifluralin vapour moves to an area with lower concentration, the trifluralin will seek to bind strongly to the new environment it enters. For this reason, trifluralin will not move extensively as a gas within the soil.

Table 8: Effect of temperature on the movement of trifluralin through a dry, alkaline, sandy soil.

Distance below the treated zone	Temperature of soil maintained for 48 hours			
	4°C	22°C	35°C	54°C
	% of trifluralin recovered (LSD = 15)			
Treated zone	100	96	85	65
0–1cm	0	4	15	33
1–2cm	0	0	0	2
Below 2cm	0	0	0	0

Source: Eureka! AgResearch (2015)

Crop safety

The safety of grain crops sown pre or post-application when using a pre-emergent herbicide is an important consideration.

There are a number of strategies that can help achieve acceptable crop safety. These include the following:

Crop tolerance

Some crops are inherently more tolerant to a particular herbicide. Usually this tolerance comes from the crop being able to rapidly detoxify that herbicide. There may also be differences between individual varieties in their ability to detoxify a particular herbicide.

An example is the use of chlorsulfuron in wheat. Wheat can quickly detoxify chlorsulfuron via metabolic processes, however if the crop is not metabolising due to waterlogging or frost, severe crop symptoms can appear as the crop is unable to detoxify the herbicide fast enough.

In some situations a herbicide safener may be able to be used to further accelerate the crop's ability to metabolise the herbicide. While safeners are more commonly used with post-emergent herbicides, a good example of safener use with pre-emergent herbicides is the application of Epivio® C or Concep® II to sorghum seed to accelerate the metabolism of s-metolachlor.

Some crop varieties have been bred to include tolerance to specific herbicides. An example are Clearfield® varieties that express tolerance to imidazolinone herbicides. This enables the use of a particular herbicide mode of action within those crops that would otherwise be lethal. It also provides rotational options in the event of a previous herbicide residue from that chemistry group remaining in the soil at sowing.

Be aware of combinations of residual herbicides. Where multiple residual herbicides are included at planting, or when there is still residual herbicide carryover in the soil and additional herbicide is applied at planting, it can be possible that the cumulative herbicide load is more difficult for the crop to metabolise, even where the herbicides are from different modes of action or when each herbicide is 'safe' on its own. This can be particularly evident where other plant stresses are also occurring, for example, waterlogging.

A good example is IMI-tolerant crops. In this scenario, 'tolerant' crops are often planted into soil where there are remaining imidazolinone residues in the soil. If these residues are taken up by the tolerant crop, the herbicide cannot bind at the target site and will not show effect from the IMI herbicide. However, the crop continues to metabolise the IMI herbicide over time and therefore diverts some metabolic capacity into degrading the IMI herbicide that may otherwise be available to degrade additional herbicides. In situations where the additional herbicide only has marginal crop safety, the combination may result in an increased chance of damage being observed. However often the additional impact of the IMI herbicide (in this example) may be dismissed as 'the crop is tolerant'.



Waterlogging in combination with pre-emergent herbicides may sometimes cause crop injury.

Photo: Mark Congreve

Differential placement

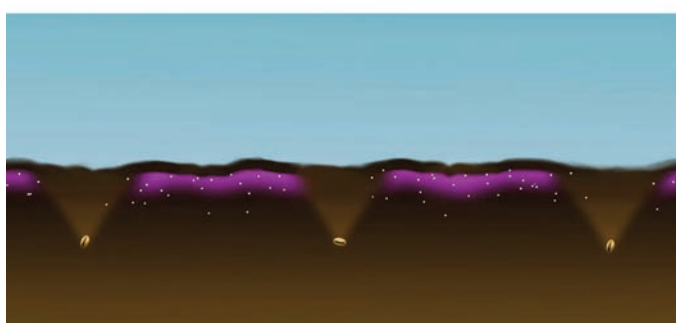
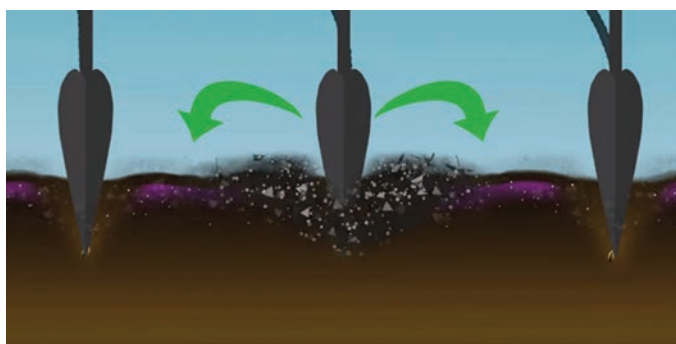
A herbicide that is toxic to the crop may still be able to be used where it can be spatially separated from the crop. If the herbicide binds sufficiently at the soil surface, it may be able to be used in a situation where the crop is sown at a depth below the herbicide band. While this may be an effective strategy for some herbicides, crop injury may still occur in situations where herbicide is moved down into or below the crop seed zone, particularly if heavy rainfall occurs as the first incorporating rainfall. Crop damage is often a function of one or more of the following: shallow seeding depth; herbicide placement in (or non-removal from) the crop row; heavy rain after sowing; soil with low binding characteristics; and/or products with high solubility and/or low binding.

Physical removal of herbicide in the furrow

The incorporation by sowing (IBS) technique used in conjunction with knife-point seeders can achieve adequate selectivity for some product/crop combinations. This is achieved by physically removing the treated soil directly above the furrow and throwing this into the inter-row, leaving an untreated area through which the crop can emerge (Figure 12). Pay careful attention to seeder set-up to ensure treated soil is not thrown into adjoining crop rows. Press wheels generally help to minimise treated soil from falling back into the furrow. Heavy rainfall after application can still cause problems if treated soil is washed into the furrow.

Regardless of the strategy employed, there may be times when an adverse crop effect still occurs when crop placement and environmental conditions allow some herbicide/crop contact. Frequently situations of crop damage coincide with the emerging crop seedling being under additional stress that slows the rate of metabolism, reducing the crop's ability to detoxify the herbicide. This is often observed in situations of waterlogging or prolonged cold or frost.

Figure 12: A well executed Incorporate by Sowing application positions the herbicide and weed seeds away from the crop row.



A well-executed IBS application will have the majority of the herbicide (purple) moved to the inter-row, with a level of soil incorporation that will reduce environmental losses. During this process, weed seeds (white dots) that are present on the soil surface in a zero-till farming system will also be positioned to the inter-row where the majority of herbicide will reside. This leaves little or no herbicide or weed seed directly over the crop seed in the planting line. For additional positional safety, cereal crop seeds should typically be planted at a minimum of 3cm below the soil level in the planting furrow, or 1.5cm for canola.

Planting systems that cannot achieve this physical separation of crop seed and herbicide (for example, low-disturbance disc seeders) are often not recommended and may not be able to be used with several pre-emergent herbicides that are otherwise toxic to the crop.

In summary

To understand how a pre-emergent herbicide will behave in the farming system, the following points should be known:

- **What weeds are in the paddock and where are the seeds?**
Knowing what is in the weed seedbank and where these seeds are located (i.e. mainly on the surface or distributed in the top 10cm) will be important in selection of the herbicide to be used and will assist in setting realistic expectations for control.
- **Is the herbicide subject to volatilisation or photodegradation?**
Knowing this will determine the incorporation strategy required to minimise loss to the environment.
- **How soluble is the herbicide?** This will influence: how much rain is required for incorporation and to wash off stubble; how easily it will be taken up by the germinating weed and crop; and susceptibility to moving deeper into the soil profile with soil water (or off-site in run-off), potentially causing crop injury or being lost to leaching.
- **What is the soil type and level of organic matter?** Sandy or low organic matter soils (low CEC) have fewer binding sites. Other factors being equal, more herbicide will be available for crop and weed uptake in lighter soil types than in a heavier or higher organic matter soil.
- **How tightly does the herbicide bind to soil and organic matter?** Herbicides that bind tightly generally stay close to where they are applied (unless the soil moves) and will persist for longer. They will also be more difficult to wash off stubble.
- **What is the soil pH?** The pH affects how long some herbicides persist for and how available they are for plant uptake and soil binding.
- **How persistent is the herbicide and how does it break down?**
This will give an indication of the expected length of residual control and plant-back constraints to sensitive crops.
- **Rainfall and temperature:** Rainfall after application is important for incorporation and to allow the herbicide to be available for root uptake. Rainfall and temperature also affect degradation.
- **Application rate:** Choice of application rate will affect the efficacy, length of effective residual and possibly crop selectivity.
- **Product labels:** Product labels are developed to reflect how herbicides behave in the soil. Always read and follow product label directions.

Key residual herbicides

Some commonly used pre-emergent herbicides and their chemical properties are discussed in this section. This information assists in understanding why they behave as they do and what considerations are important in their performance as a pre-emergent herbicide.

For herbicides not covered in detail in this section, Table 9 lists the important properties of the majority of pre-emergent herbicides used in Australian grain production². Readers should be able to interpret these properties in relation to the principles outlined in the initial chapters of this manual and therefore understand which drivers are most likely to be important for any particular herbicide and situation.

Unless otherwise stated, values quoted are specific to the active ingredients in the tables below and were sourced from the Pesticide Properties Database, which can be found at sitem.herts.ac.uk/aeru/iupac/index.htm (University of Hertfordshire, 2006-2023). The database was accessed on 26 June 2023.

Group 1

Mode of action: Group 1 herbicides inhibit the acetyl-CoA carboxylase (ACCase) enzyme which blocks fatty acid synthesis within the plant. ACCase is most active in meristematic regions of the young plant where new cell growth is occurring. As a result, Group 1 herbicides are most effective on young weeds. Cell production ceases almost immediately, however it is typically one to two weeks before symptoms are visible.

There are three sub-groups of Group 1 herbicides used in Australian grain production. These are:

- aryloxyphenoxypropionates (fops);
- cyclohexanediones (dims); and
- phenylpyrazoles (dens).

General properties: Group 1 herbicides are primarily taken up by foliar absorption and are registered for the post-emergent control of grass weeds in a range of crops and situations. They are not generally considered as pre-emergent herbicides. They have been referenced here and in Table 9 as some herbicides from this group do have a level of soil activity, resulting in plant-back constraints.

Breakdown of the 'dim' herbicides occurs via microbial degradation and is often relatively fast, with generally less residual activity than for 'fop' herbicides. Plant-back constraints to monocot crops are normally measured in weeks for the 'dims' but are often poorly defined on product labels, as typical use patterns are early in-crop and there has historically been little need to define re-cropping intervals more accurately.

Breakdown of 'fops' typically is a two-stage process. Most 'fops' are applied in the ester form which generally undergoes rapid hydrolysis and conversion to the acid form. Once in the acid form, microbial degradation becomes the primary breakdown pathway in the soil. The speed of breakdown varies between different fop herbicides, with some of the longer plant-back constraints measured in terms of weeks or months. Conditions that favour good microbial activity, (that is, warm and moist) will typically lead to the fastest breakdown. Refer to product labels for plant-back information for sensitive crops.

Group 2

Mode of action: Group 2 herbicides work by inhibiting the acetolactate synthase (ALS) enzyme. ALS occurs throughout the plant, however is most active in meristematic regions of the plant where new cell growth is occurring. Group 2 herbicides are most effective on young weeds. Enzyme inhibition is rapid, usually within hours; however, it typically takes 1 to 2 weeks for visual herbicide symptoms to appear.

There are three main sub-groups of ALS inhibitors used in Australian grain production:

- sulfonyleureas (SUs);
- imidazolinones (IMIs); and
- triazopyrimidines (TPs).

There can be significant differences between selectivity, spectrum of activity and binding sites between the groups and between individuals within the three groups. This is primarily due to different chemical structures allowing for different metabolic pathways. A major practical difference between groups that affects their environmental availability comes from how they are degraded under various soil pH conditions.

Resistance arising from an altered target site mutation is very common within Group 2 herbicides. Non-target site metabolic resistance is also present and increasing. High levels of resistance are widespread in many weed species within Australia.

General properties: Most Group 2 herbicides have high solubility and are weak acids, being systemic within the xylem and phloem once inside the plant. Many can enter the plant via foliar uptake so are suited to post-emergent use. However, a number of molecules from within this group also have soil residual activity, with substantial uptake via root absorption.

Most ALS inhibitor herbicides have broad-spectrum activity on dicots. Activity on monocots varies between individual herbicides, depending on the ability of the monocot species to rapidly metabolise the specific herbicide.

² Several herbicides covered in Table 9 were included as their registered label contains plant-back constraints to rotational crops, even though some of these products are generally not considered to provide substantial residual activity on weeds.

The persistence of different members of this herbicide group varies considerably and this differential persistence, combined with differential monocot selectivity, has seen many different Group 2 herbicides commercialised within the Australian grains industry.

For many of the sulfonylureas, hydrolysis is the primary breakdown mechanism. This can be relatively fast or quite slow, depending upon the individual compound. However, as the soil pH becomes alkaline this reaction slows, or stops, and then slow microbial degradation becomes the primary method of breakdown. For this reason, many sulfonylureas persist much longer in alkaline soils, where hydrolysis is very slow or does not occur.

With imidazolinone herbicides, microbial breakdown is the primary route of degradation and is typically very slow for most imidazolinones. Persistence in the soil increases with lower soil pH (acidic soils) as binding increases, making the herbicide less available for microbial breakdown.

Breakdown of triazolopyrimidines occurs via microbial degradation and can be quite fast for some molecules and moderate for others. This sub-group is generally less sensitive to soil pH than the other groups of ALS herbicides.

Sulfonylureas

Chlorsulfuron					
Getting to the soil			When in the soil		
Solubility (mg/L)	12,500	High	Binding (K_{oc})	36 (k_{loc})	Mobile
Vapour pressure (mPa)	3.07×10^{-6}	Non-volatile	Half-life (DT_{50})	11–185 (av. 36)	Moderately persistent
Photodegradation	Negligible		Mobility	Mobile in the soil Potential to leach, especially at higher pH	
Breakdown	Hydrolysis cleaves the sulfonylurea bridge with the speed of breakdown increasing with lower soil pH. Microbial breakdown is slow				

Practical considerations:

- With volatility and photodegradation both being low, the herbicide will not break down rapidly on the soil surface after application.
- Solubility is high and binding to organic matter is low, assisting rainfall to wash herbicide off the stubble.
- Speed of breakdown depends on soil pH and moisture content. Plant-back to sensitive crops can be very long in alkaline soils, especially under dry summer conditions. Observe label constraints for time and rainfall requirements.
- This also means the compound is freely available for root uptake and translocation once in the soil, however there is potential for leaching down the profile following large rainfall events, particularly in alkaline soils. If applied to dry soil without mechanical incorporation and followed by a significant rainfall event during emergence, there is potential for it to move down the profile and damage germinating crops.

Metsulfuron					
Getting to the soil			When in the soil		
Solubility (mg/L)	2790	High	Binding (K_{oc})	12 (k_{oc})	Very mobile
Vapour pressure (mPa)	1.4×10^{-8}	Non-volatile	Half-life (DT_{50})	7–37 (av. 13)	Non-persistent
Photodegradation	Negligible		Mobility	Mobile within the soil however rapidly breaks down	
Breakdown	Non-microbial hydrolysis occurs relatively rapidly, particularly at lower soil pH and higher soil moisture and temperature				

Practical considerations:

- With volatility and photodegradation both being low, the herbicide will not break down rapidly on the soil surface after application.
- Due to rapid hydrolysis, plant-back constraints are often less than for some other sulfonylureas.
- Solubility is high and binding to soil is low, so will be freely available in the soil. However, soil persistence is typically short.

Sulfosulfuron

Getting to the soil			When in the soil		
Solubility (mg/L)	1627	High	Binding (K_{oc})	5–89 (av. 33) (k_{oc})	Mobile
Vapour pressure (mPa)	3.05×10^{-5}	Non-volatile	Half-life (DT_{50})	29–75 (av.45)	Non-persistent
Photodegradation	Can be significant		Mobility	Will be freely available in the soil water	
Breakdown	Hydrolysis is the major breakdown pathway in low pH soils and can be relatively rapid. In alkaline soils, breakdown via hydrolysis is slow, with microbial degradation becoming significant at higher pH levels.				

Practical considerations:

- Losses to volatility are insignificant; however, loss to photodegradation can be significant if there is an extended period before incorporation. Labels recommend incorporation by sowing into moist soil when being used as a pre-emergent application. If tank mixing with tri-allate or trifluralin then follow label recommendations for those herbicides.
- Solubility is high and binding to organic matter is low, assisting rainfall to wash herbicide off the stubble.
- This also means the compound is freely available for root uptake and translocation once in the soil, however there is potential for leaching down the profile following large rainfall events. If applied to dry soil without mechanical incorporation, and followed by a significant rainfall event during emergence, there is the potential to move down the profile and damage germinating crops.
- Speed of breakdown depends on soil pH and moisture content. Plant-back to sensitive crops can be very long in alkaline soils, especially under dry summer conditions. Observe label constraints for time and rainfall requirements.

Triasulfuron

Getting to the soil			When in the soil		
Solubility (mg/L)	815	High	Binding (K_{oc})	60	Mobile
Vapour pressure (mPa)	2.1×10^{-3}	Non-volatile	Half-life (DT_{50})	16–92 (av. 39)	Non-persistent
Photodegradation	Insignificant		Mobility	High solubility and low binding increases availability in the soil water	
Breakdown	Hydrolysis is the major breakdown pathway in neutral and low pH soils. In alkaline soils, breakdown via hydrolysis is very slow and at high pH levels, slow microbial degradation becomes the primary route of dissipation.				

Practical considerations:

- With volatility and photodegradation both being low, the herbicide will not break down rapidly on the soil surface after application.
- Solubility is high and binding to organic matter is low, so will be readily washed off stubble following rainfall.
- This also means the herbicide is freely available for root uptake and translocation once in the soil, however there is potential for leaching down the profile following large rainfall events. If applied to dry soil without mechanical incorporation and followed by a significant rainfall event during emergence, there is the potential to move down the profile and damage germinating crops.
- Speed of breakdown depends on soil pH and moisture content. Plant-back to sensitive crops can be very long in alkaline soils, especially under dry summer conditions. Observe label constraints for time and rainfall requirements.

Imidazolinones

Imazapic

Getting to the soil			When in the soil		
Solubility (mg/L)	2230	High	Binding (K_{oc})	137	Moderately mobile
Vapour pressure (mPa)	0.01	Non-volatile	Half-life (DT_{50})	31–410 (av. 232)	Persistent
Photodegradation	Negligible		Mobility	Moderate due to high solubility and only moderate binding	
Breakdown	Predominantly microbial.				

Practical considerations:

- With volatility and photodegradation both being low, the herbicide will not breakdown rapidly on the soil surface after application.
- High solubility and only moderate binding allows for the herbicide to be readily washed off stubble and incorporated with rainfall.
- Moderate binding prevents excessive losses via leaching. Binding increases at lower soil pH.
- Very persistent due to slow microbial breakdown, especially under conditions of low soil pH and low soil moisture. Substantial plant-back constraints exist. Observe label constraints for pH, time and rainfall requirements.

Imazethapyr

Getting to the soil			When in the soil		
Solubility (mg/L)	1400	High	Binding (K_{oc})	52	Mobile
Vapour pressure (mPa)	1.3×10^{-2}	Non-volatile	Half-life (DT_{50})	7–290 (av. 51)	Moderately persistent
Photodegradation	Negligible		Mobility	Mobile in the soil water	
Breakdown	Predominantly microbial.				

Practical considerations:

- With volatility and photodegradation both being low, the herbicide will not breakdown rapidly on the soil surface after application.
- Imazethapyr has post-emergent and pre-emergent activity. Once in the plant it is readily translocated.
- Low binding in neutral and alkaline soils means the herbicide is likely to be freely available in soil water in many soils. Binding increases in soils with higher organic matter and soils where pH is below 6.5.
- Persistence is moderate, however it can be quite long under conditions of low soil pH and low soil moisture, where binding increases and microbial activity is reduced. Substantial plant-back constraints to susceptible crops exist. Observe label constraints for pH, time and rainfall requirements.
- Crop selectivity comes from rapid metabolism in tolerant plants.

Triazolopyrimidines

Flumetsulam

Getting to the soil			When in the soil		
Solubility (mg/L)	5650	High	Binding (K_{oc})	28	Mobile
Vapour pressure (mPa)	3.7×10^{-7}	Non-volatile	Half-life (DT_{50})	45	Moderately persistent
Photodegradation	Negligible		Mobility	Mobile in the soil water	
Breakdown	Predominantly microbial.				

Practical considerations:

- Flumetsulam is primarily used for post-emergent application in Australia, however in other countries it is primarily used as a pre-emergent herbicide.
- High solubility; easily taken up by roots and translocated within the plant.
- Crop selectivity comes from rapid metabolism in tolerant plants.
- Moderate persistence leads to plant-back constraints (see label for details). Application rate will affect length of crop rotation restrictions in some situations. Breakdown will be fastest in soils with good microbial activity i.e. warm, moist soils.

Group 3

Mode of action: Group 3 herbicides bind to the major microtubule protein tubulin, which causes a loss of microtubule structure and inhibits mitosis. Often this can be observed as swelling/clubbing of the roots' tips as cells cannot divide or elongate.

Within Group 3, there are four subclasses registered for use in Australia, however the primary classes used in broadacre agriculture are:

- dinitroanilines (DNAs) for example, pendimethalin, trifluralin; and
- benzamides, for example, propyzamide.

Resistance to trifluralin is widespread in ryegrass throughout many states within Australia.

General properties: DNA herbicides characteristically have higher volatility, particularly on wet soils, and may also be subjected to photodegradation, particularly under warm conditions. Incorporation or soil coverage is recommended to minimise herbicide loss.

Use patterns developed in the 1970s and 1980s relied on full mechanical incorporation – often with multiple passes. More recently, Australian use patterns have been developed enabling use of DNA herbicides in reduced and no-till farming.

For example, trifluralin can be applied immediately in front of the seeder, using this method to incorporate the herbicide and sow the crop in the one pass. The 'incorporate by sowing' technique (IBS) uses knife-point seeders set up to throw soil into the inter-row to cover the herbicide and reduce volatilisation losses. This also removes treated soil from above the crop row, which increases crop selectivity, enabling higher rates than could have been used in the 'old' full incorporation use pattern. These higher application rates also provide some compensation for volatility losses from less than ideal incorporation and tie-up on stubble. In no-till systems where most weed seed is on or near the soil surface, the levels of weed control achieved from a well-executed, high-rate IBS system can be higher than that achieved in the older 'lower rate – full incorporation' system where weed seed and herbicide were diluted by mechanical mixing through the surface zone.

DNA herbicides typically have very low solubility and very strong binding to soil and organic matter. This can result in excessive 'tie-up' on stubble or plant material present at application, which is then effectively lost, as rainfall will be unable to wash it off the organic matter. The lipophilic nature, very low solubility and strong binding does not favour root uptake from herbicide available in the soil moisture. Primary entry into the germinating seedling comes

via gaseous absorption through the roots and the coleoptile node or hypocotyl, as the seedling moves through the herbicide band.

Microbial degradation is the primary breakdown route.

CROP SELECTIVITY AND DNA HERBICIDES

Herbicide selectivity comes from species tolerance (many broadleaf crops are more tolerant) and spatial separation of sensitive crop species (for example, wheat, barley) from the herbicide. Spatial separation is achieved by using techniques such as sowing below the treated band and, with 'incorporate by sowing' applications, stripping away treated soil from above the sowing row.

For many grass weeds and cereal crops such as oats, maize and sorghum, the mesocotyl elongates during germination and this pushes the coleoptile node, from which the secondary roots grow, towards the surface (see Figure 11). In DNA susceptible species, having the secondary roots and the coleoptile node and mesocotyl (areas sensitive to DNA herbicide uptake) closer to the herbicide band increases availability for herbicide uptake by the germinating seedling.

In wheat and barley, the coleoptile node (and therefore primary and secondary root development) stays much closer to the seed, allowing for greater separation between the herbicide and the roots and coleoptile node that are sensitive to DNA herbicide uptake.

In zero-till farming systems when using IBS application with knife points, the herbicide band is kept very close to the soil surface, maximising spatial separation of wheat and barley. This permits increased application rates to be used.

Where wheat or barley are to be sown following a pre-emergent DNA herbicide application, seeder set-up and operational speed needs to be carefully maintained and balanced with soil conditions and sowing boot design. Seeding equipment must provide adequate separation between the treated soil and cereal crop. Well set-up equipment provides sufficient soil movement to cover the inter-row area to reduce volatility losses, while not throwing soil too far and into the furrow of the adjoining crop row. Tined implements are far better at meeting these requirements than many low-disturbance disc seeders, a requirement that is often reflected on product labels for the IBS technique. Press wheels help prevent treated soil from falling back into the furrow.

While DNA herbicides are tightly bound to the soil, should a significant rainfall event occur as the first incorporating rainfall, there is a risk that soil with bound herbicide can be washed into the sowing furrow and cause damage to the emerging cereal crop.

Dinitroanilines

Pendimethalin

Getting to the soil			When in the soil		
Solubility (mg/L)	0.33	Low	Binding (K_{oc})	10,241–36,604 (av. 17,491)	Non-mobile
Vapour pressure (mPa)	3.34	Volatile	Half-life (DT_{50})	40–187 (av. 100)	Moderately persistent
Photodegradation	Can be subject to photodegradation if not incorporated		Mobility	Binds tightly to soil and organic matter	
Breakdown	Microbial breakdown				

Practical considerations:

- Can be subjected to losses from volatility and photodegradation. Follow label recommendations for incorporation instructions.
- Can be tied up on stubble or plant material present (for example, weeds) during application.
- Once incorporated in the soil, pendimethalin will be bound tightly near the soil surface or where it has been placed, providing extended control.
- Rotational crop constraints apply. Follow label directions. Full cultivation to 15cm depth will assist in diluting residues through the soil profile.

Trifluralin

Getting to the soil			When in the soil		
Solubility (mg/L)	0.22	Low	Binding (K_{oc})	15,800	Non-mobile
Vapour pressure (mPa)	9.5	Volatile	Half-life (DT_{50})	35–375 (av. 170)	Persistent
Photodegradation	Can be subject to photodegradation if not incorporated		Mobility	Binds tightly to soil and organic matter	
Breakdown	Microbial breakdown				

Practical considerations:

- Can be subjected to losses from volatility and photodegradation. Follow label recommendations for incorporation instructions.
- Strongly tied up on stubble or plant material present (for example, weeds) during application.
- Once incorporated in the soil, trifluralin will remain bound where it has been placed and expected to provide extended control.
- Microbial degradation is slow, especially under cool, dry conditions. Rotational crop constraints apply. Follow label directions.
- When using cultivation for incorporation, avoid cereal varieties with short coleoptiles, or seed treatments that shorten the coleoptile and ensure seeds are sown below the herbicide band.

Benzamides

Propyzamide

Getting to the soil			When in the soil		
Solubility (mg/L)	9	Low	Binding (K_{oc})	548–1340 (av. 840)	Slightly mobile
Vapour pressure (mPa)	0.058	Non-volatile	Half-life (DT_{50})	14–271 (av. 51)	Persistent
Photodegradation	Can be subject to photodegradation if not incorporated		Mobility	Binds tightly to soil and organic matter	
Breakdown	Volatilisation and photodegradation can be significant without incorporation, especially under warm, dry conditions. Microbial and non-microbial dissipation occur in the soil.				

Practical considerations:

- Tie-up on stubble will be significantly less than for trifluralin, with some of the propyzamide being able to be washed off the stubble and into the soil following adequate rainfall.
- Unlike the DNAs, which are primarily taken up via gaseous diffusion into the roots and coleoptile node, propyzamide is primarily taken up by the roots from herbicide dissolved in the soil water. Low solubility means that good soil moisture is required for the period of weed control for herbicide uptake.
- Requires incorporation by sowing and rainfall (25mm) soon after application to reduce photodegradation and maximise herbicide performance.
- Relatively low solubility and significant binding will generally keep the herbicide near the soil surface. Weed seeds germinating close to the surface (as is usually the case in zero/minimal till farming), are likely to be well controlled, however weed seeds germinating from depth may keep their roots below treated soil.

Group 4

Mode of action: Group 4 contains the synthetic auxin herbicides. When introduced into the plant they cause uncontrolled and abnormal cell division and growth, leading to cell destruction, or they may inhibit cell division, particularly in the meristematic regions of the plant. Typical symptoms include twisting of new growth, before plant necrosis.

There are five subclasses of Group 4 herbicides registered in Australia:

- phenoxy carboxylic acids (for example, 2,4-D, MCPA);
- benzoic acids (for example, dicamba);
- pyridine carboxylic acids (for example, aminopyralid, clopyralid, fluroxypyr, triclopyr, picloram);
- quinoline carboxylic acids (for example, quinclorac); and
- arylpicolinates (for example, halauxifen).

Dicamba has very short soil persistence and therefore does not provide effective residual control. Quinclorac is only registered for use in turf in Australia.

Phenoxy and arylpicolinates have short persistence and may have short plant-back constraints (usually measured in days to weeks), however they generally do not have any significant pre-emergent activity in grain crops at registered use rates. Pyridine carboxylic acids may provide residual activity.

Despite widespread use in Australia since the 1960s, resistance to this mode of action has been limited until relatively recently. Confirmed resistance exists in the phenoxy subclass in wild radish (1999), Indian hedge mustard (2005), capeweed (2015) and, to

multiple Group 4 subclasses, in sow thistle (2015). The number of wild radish populations with resistance to Group 4 and resistance to other multiple modes of action is increasing rapidly, and poses a significant and major weed threat to crop production.

Typically Group 4 herbicides will be applied in either the ester or salt (amine) form. When in the soil water, or when taken up by the plant, they will be converted to the parent acid, which is the herbicidally active form. When considering soil movement and carryover, both the applied form and the parent acid need to be considered.

General properties of the pyridine carboxylic acids: The pyridine herbicides are typically suited to foliar uptake as the primary pathway into the plant. However most compounds have high solubility and relatively low binding, providing potential for root uptake.

Persistence is typically moderate for many of the pyridines, however rotational crop constraints can be significant, especially at higher application rates and under conditions that do not favour microbial breakdown. Warm, moist conditions provide for fastest breakdown. For mobile compounds, leaching can also be significant.

The main exception from this group is fluroxypyr. Fluroxypyr, in the applied fluroxypyr-meptyl form, has very low solubility and tight binding. Small amounts of unbound herbicide convert to fluroxypyr acid which is more persistent. However, insufficient concentration of the acid is present to provide soil uptake in most situations, meaning minimal rotational crop constraints apply.

Pyridine carboxylic acids

Clopyralid acid					
Getting to the soil			When in the soil		
Solubility (mg/L)	7850	High	Binding (K _{oc})	3–7 (av. 5)	Very mobile
Vapour pressure (mPa)	1.36 [#]	Volatile	Half-life (DT ₅₀)	2–14 (av. 8) [EU studies] 12–70 (av. 40) [US studies] [#]	Moderately persistent
Photodegradation	Negligible		Mobility	Potential to move with soil water	
Breakdown	Microbial breakdown is significant				

[#] Shaner (2014).

Practical considerations:

- Very high solubility and very low binding allows the compound to be freely available in the soil water phase, however there is increased binding over time. This increased binding with time means that when higher application rates are applied the half-life increases, whereas if lower use rates are applied the half-life is shorter.
- High bioavailability (potential to move with soil moisture) means that some herbicide can move down the soil profile, especially on light-textured soils. The herbicide component moving to depth will typically have much slower degradation as microbial activity is reduced at depth. This can result in extended carryover which may only be observed when the crop roots reach the herbicide deeper in the profile.
- Due to these factors persistence can be extended, especially in situations that do not favour microbial degradation (i.e. dry summers). Crop rotation restrictions can occur, especially after higher application rates. Follow label details for plant-back considerations.

Fluroxypyr-meptyl

Getting to the soil			When in the soil		
Solubility (mg/L)	0.136	Low	Binding (K_{oc})	19,550 51–81 (av. 68) (k_{loc}) for fluroxypyr acid.	Non-mobile
Vapour pressure (mPa)	0.01	Non-volatile	Half-life (DT_{50})	3 34–68 (av. 51) for fluroxypyr acid.	Non-persistent
Photodegradation	Not significant		Mobility	Breaks down rapidly to fluroxypyr acid, which is more mobile.	
Breakdown	Relatively fast microbial degradation				

Practical considerations:

- Fluroxypyr is included here to highlight that it is different to the other pyridine herbicides in its applied form.
- Fluroxypyr-meptyl reaching the soil has very low solubility and tight binding. Available unbound herbicide in the soil water rapidly converts to the acid form, which is significantly more mobile and more persistent. Soil uptake of fluroxypyr is minimal in most situations.

Picloram

Getting to the soil			When in the soil		
Solubility (mg/L)	488	Moderate	Binding (K_{oc})	13	Very mobile
Vapour pressure (mPa)	2×10^{-3}	Non-volatile	Half-life (DT_{50})	20–49 (av. 34) [EU studies] 20–300 (av. 90) [#] [US studies]	Moderately persistent
Photodegradation	Can be significant if applied to dry soil surface		Mobility	Potential to leach, especially in sandy or low organic matter soils	
Breakdown	Photolysis and leaching can be significant pathways for loss. Slow microbial degradation. Fastest under warm, moist conditions.				

[#] Shaner (2014).

Practical considerations:

- Picloram is an effective herbicide when applied via foliar application, however can also be a useful pre-emergent herbicide on some weeds.
- Photodegradation can occur if applications are made to dry soil and incorporation by rainfall or cultivation does not occur for a number of weeks.
- Very high solubility and very low binding allows the compound to be freely available in the soil water phase, however there is increased binding over time. This increased binding with time means that when higher application rates are applied the half-life increases, whereas if lower use rates are applied the half-life is shorter.
- High bioavailability (potential to move with soil moisture) means that some herbicide can move down the soil profile, especially on light-textured soils. The herbicide component moving to depth will typically have much slower degradation as microbial activity is reduced at depth. This can result in extended carryover which may only be observed when the crop roots reach the herbicide deeper in the profile.
- Due to these factors persistence can be extended, especially in situations that do not favour microbial degradation (i.e. dry summers). Crop rotation restrictions can occur, especially after higher application rates. Follow label details for plant-back considerations.

Group 5

Mode of action: Group 5 herbicides work by inhibiting photosynthesis by binding at the photosystem II complex.

There are many subclasses of Group 5 mode of action. The subclasses of primary importance for pre-emergent use in Australian broadacre agriculture include:

- triazines (for example, atrazine, prometryn, simazine, terbutylazine);
- triazinones (for example, metribuzin); and
- ureas (for example, diuron, fluometuron).

Group 5 resistant wild radish, ryegrass, barnyard grass, Indian hedge mustard and liverseed grass have been identified in Australia, however, as of 2023 they are typically infrequent and the extent of the spread of resistant populations has not developed as fast as it has to other modes of action.

General properties: Many Group 5 herbicides can be taken up by the plant either by root or foliar uptake, however some (for example, simazine) are primarily root uptake.

Solubility of the triazines and ureas is typically low; therefore, very good soil moisture is usually required for effective root uptake from pre-emergent applications. When triazines and ureas are applied as a post-emergent foliar application, there is little movement outside of the treated leaf. Additional herbicide reaching the soil following a post-emergent application may be

taken up by roots and transported within the xylem.

The triazinone herbicide metribuzin has high solubility so therefore is more easily taken up by plant roots and through foliage and is readily translocated in the xylem.

Microbial breakdown occurs across the subclasses of Group 5 chemistry, however this is typically slow, especially under cool or dry conditions that do not encourage microbial populations.

For the triazine group, breakdown via hydrolysis also occurs. This breakdown path is much faster than microbial degradation and becomes the primary pathway on acidic and neutral soils. As soil pH increases, hydrolysis slows or stops, which then leaves slow microbial degradation as the primary method of breakdown. This leads to increased persistence of triazines on alkaline soils.

Where there has been long-term, repeated use of triazine herbicides, and especially in situations where there is good soil organic matter, a process of 'enhanced microbial breakdown' can occur. Enhanced microbial breakdown occurs where there is a build-up of soil microflora with an enhanced capability to detoxify the herbicide. Enhanced microbial degradation of triazines has been reported from multiple locations in Australia.

Differential selectivity between species is due to rapid detoxification. For example, some crops such as sorghum and maize are able to rapidly metabolise some triazine herbicides.

Triazines

Atrazine					
Getting to the soil			When in the soil		
Solubility (mg/L)	35	Low	Binding (K_{oc})	89–513 (av. 100)	Moderately mobile
Vapour pressure (mPa)	0.039	Non-volatile	Half-life (DT_{50})	6–108 (av. 60*)	Moderately persistent
Photodegradation	Can be moderate, especially where not incorporated by rainfall		Mobility	Can leach under high rainfall due to only moderate binding	
Breakdown	Microbial degradation is significant but typically slow. Under repeated applications microbial degradation has been shown to be accelerated. Hydrolysis is the primary breakdown pathway at soil pH below 6.5, however is slow at soil pH above 7.5				

[#] Shaner (2014).

Practical considerations:

- Unlikely to be lost via volatilisation after application. Losses to photodegradation can occur if not incorporated, especially if conditions remain dry after application.
- Low solubility means that substantial rainfall will be required to move herbicide off stubble and into the soil. Adequate rainfall will be required to wet the top 5cm of soil to incorporate the herbicide. If rainfall or irrigation is not expected then mechanical incorporation should be considered within a few days following application.
- Low solubility means that ongoing good soil moisture is required for uptake by plant roots. Under dry conditions weed control is likely to be reduced.
- Soil binding is moderate, however it can be weak, especially on sandy soils, soils with low organic matter or alkaline soils. This can lead to herbicide moving down the profile with substantial rainfall events and may move to below the root zone of the weeds.
- Moderately persistent, with persistence increasing under conditions of high soil pH and low soil moisture. Application rates are typically high, so substantial plant-back constraints are likely to exist for sensitive crops.
- Enhanced microbial degradation has been shown to occur where regular herbicide application occurs on the same soil.
- Has both root and shoot uptake, however translocation only occurs in an upward direction.

Simazine

Getting to the soil			When in the soil		
Solubility (mg/L)	5	Low	Binding (K_{oc})	130	Moderately mobile
Vapour pressure (mPa)	8.1×10^{-4}	Non-volatile	Half-life (DT_{50})	27–102 (av. 90)	Moderately persistent
Photodegradation	Can degrade, especially if conditions are dry after application		Mobility	Moderate binding reduces availability, however can be mobile in sandy or low organic matter soils	
Breakdown	Slow microbial degradation is the primary pathway in high pH soils. In neutral to acid soils, breakdown by non-microbial hydrolysis is more rapid than microbial breakdown.				

Practical considerations:

- Very low solubility and the possibility of photodegradation requires good rainfall after application to achieve suitable incorporation. Good soil moisture for the weeks after application is required for good weed control.
- Less binding in sandy or low organic matter soils may lead to more availability of the herbicide, increasing the risk of crop injury in susceptible crops grown on these soils.
- Persistence leads to plant-back constraints, particularly in alkaline soils where the speed of hydrolysis is substantially reduced.
- Uptake is primarily via the roots, with negligible foliar uptake.

Terbuthylazine

Getting to the soil			When in the soil		
Solubility (mg/L)	7	Low	Binding (K_{oc})	231 (k_{loc})	Moderately mobile
Vapour pressure (mPa)	0.152	Non-volatile	Half-life (DT_{50})	16–149 (av. 22)	Non-persistent
Photodegradation	Limited, although may occur where not incorporated by rainfall		Mobility	Moderate binding and low solubility reduces mobility and leaching	
Breakdown	Hydrolysis is the primary pathway in acidic soils. Slow microbial degradation is the primary pathway in alkaline soils.				

Practical considerations:

- Unlikely to be lost via volatilisation after application unless soil remains dry for a number of weeks. Can be subject to photodegradation when applied to warm, dry soils without incorporation.
- Very low solubility means that substantial rainfall (20–30mm) will be required to move herbicide off stubble and into the soil to incorporate the herbicide.
- Very low solubility means that good soil moisture is required to permit uptake by plant roots. Under dry conditions weed control is likely to be reduced.
- Soil binding is stronger than atrazine and solubility lower, which is likely to keep the product closer to the soil surface and less likely to leach down the profile. However, if heavy rainfall occurs on lighter/sandy soils, then herbicide could still move into the root zone of germinating crops and crop damage may result. Stronger soil binding means that terbuthylazine may provide more consistent control of shallow or surface-germinating weeds compared to atrazine and may also provide additional safety for deeper sown crops.
- The soil persistence of terbuthylazine is typically less than for some other triazines, however can be greatly extended on some soil types. Where dry conditions are experienced following application, plant-backs may need to be extended.

Triazinones

Metribuzin

Getting to the soil			When in the soil		
Solubility (mg/L)	1100 [#]	High	Binding (K_{oc})	27–82 (av. 48) (k_{loc})	Mobile
Vapour pressure (mPa)	0.121	Non-volatile	Half-life (DT_{50})	14–28 [#] (av. 19)	Non-persistent
Photodegradation	Insignificant		Mobility	Binds tighter to organic matter than soil. Binding decreases in alkaline soils.	
Breakdown	Microbial breakdown in the soil is the primary pathway				

[#] Shaner (2014).

Practical considerations:

- Unlikely to be significantly lost via volatilisation or photodegradation after application before suitable incorporation by rainfall.
- High solubility and low binding allows metribuzin to be mobile in the soil water phase.
- Availability in the soil is influenced by soil type, pH, organic matter and climate. Metribuzin will be most available (for both plant uptake and leaching) in sandy soils, alkaline soils and low organic matter soils. Label constraints may limit application in these situations and/or recommend lower application rates, so as to minimise crop injury from pre-emergent applications.
- Breakdown is typically relatively fast, however will be slowest in cool, dry conditions. Relatively short persistence does not normally influence the choice of crop the following year after application.

Ureas

Diuron

Getting to the soil			When in the soil		
Solubility (mg/L)	36	Low	Binding (K_{oc})	238–1750 (av. 680)	Slightly mobile
Vapour pressure (mPa)	1.15×10^{-3}	Non-volatile	Half-life (DT_{50})	54–792 (av. 229)	Persistent
Photodegradation	Limited, although may occur where not incorporated by rainfall		Mobility	Significant binding and low solubility reduces mobility and leaching in clay/high OM soils	
Breakdown	Microbial degradation is the primary breakdown pathway. Hydrolysis is insignificant.				

Practical considerations:

- Unlikely to be lost via volatilisation after application unless soil remains dry for a number of weeks, however some photodegradation may occur in this situation.
- Low solubility means that substantial rainfall will be required to move herbicide into the soil and adequate rainfall will be required to wet the top 5cm of soil to incorporate the herbicide.
- Relatively tight binding to organic matter may tie up a significant portion of applied herbicide under high stubble loads.
- Low solubility means that good soil moisture is required to permit uptake by plant roots. Under dry conditions, weed control is likely to be reduced.
- Primarily taken up by root absorption. Foliar uptake is less significant.
- Soil binding varies with soil type, in particular in relation to the clay and organic matter levels of the soil. In low clay/low organic matter soils, diuron may be loosely bound and hence subject to movement down the profile with heavy rainfall, with increased potential for crop injury.
- Soil persistence is relatively high and significant plant-back requirements result.

Group 12

Mode of action: Group 12 herbicides cause inhibition of the phytoene desaturase enzyme (PDS inhibitors) within the chloroplasts. This prevents carotenoid synthesis which results in the characteristic bleaching effects typical of this mode of action.

Group 12 herbicides are typically effective via foliar application. However, some also demonstrate 'pre-emergent' activity when the shoots of germinating weeds take up the herbicide. Where control is achieved as a pre-emergent application, germinating weeds stop growing within days and may appear bleached before tissue necrosis, eventually leading to plant death.

The pyridazinone subclass contains the horticultural herbicide norflurazon (not covered in this manual). The pyridinecarboxamide subclass contains picolinafen and diflufenican which can persist in the soil. Diflufenican may provide some limited activity on germinating weeds under certain conditions.

Resistance to this mode of action has been confirmed in Indian hedge mustard and wild radish.

Diflufenican					
Getting to the soil			When in the soil		
Solubility (mg/L)	0.05	Low	Binding (K_{oc})	1622–2369 [#]	Slightly mobile
Vapour pressure (mPa)	4.25 x 10 ⁻³	Non-volatile	Half-life (DT ₅₀)	105–210 [#]	Persistent
Photodegradation	Insignificant		Mobility	Binds tightly at the soil surface	
Breakdown	Metabolic degradation is slow.				

[#] Shaner (2014).

Practical considerations:

- Tight binding and very low solubility sees the herbicide binding tightly at the soil surface.
- Rapid metabolism by cereals allows for crop selectivity when applied as a post-emergent application.
- Where registered, selectivity to legume and pulse crops comes from delaying application until seedlings are established and from sowing depth i.e. having roots established below the main herbicide band (see label for details). Some temporary crop effect may be observed from the over-the-top application, especially if the crop is under additional stress from other factors that may reduce the speed of metabolism.
- Low solubility and high lipophilicity means that translocation within the plant is minimal. For post-emergent application this means excellent spray coverage is required against small weeds. Tolerance increases rapidly with plant age.
- For pre-emergent activity, good soil moisture is required for consistent results. Pre-emergent weed control is achieved primarily by uptake via the hypocotyl of the germinating weed moving through the treated soil. Weeds germinating from below the herbicide band on the soil surface may escape control.
- As the herbicide is tightly bound to the soil surface, thorough cultivation prior to sowing rotational crops is likely to dilute residues further by mixing soil through the profile.

Group 13

Mode of action: Group 13 herbicides inhibit deoxy-D-xylulose phosphate (DOXP) which is a key enzyme required in the early stage of the methyl-D-erythritol phosphate (MEP) pathway. The MEP pathway is one of two pathways that plants utilise to produce isoprenoid precursors required for the production of geranylgeranyl pyrophosphate (GGPP). GGPP is the key precursor for production of carotenoids, gibberellins, tocopherols and chlorophyll.

Visual herbicide symptoms appear as bleaching in some species, or a bright magenta discoloration in other species (for example, bixlozone on annual ryegrass).

Herbicides with the Group 13 mode of action that are available in Australia include bixlozone and the rice/horticultural herbicide clomazone.

To date, no resistance to the Group 13 mode of action has been reported in Australia.

Bixlozone

Getting to the soil			When in the soil		
Solubility (mg/L)	40	Low	Binding (K_{oc})	315–541 (K_{loc})	Moderate mobility
Vapour pressure (mPa)	1.1	Slightly volatile	Half-life (DT_{50})	11–245 (av. 99)	Persistent
Photodegradation	Not expected to be significant		Mobility	Moderate	
Breakdown	Microbial degradation.				

Practical considerations:

- The current Australian label for bixlozone (for example, Overwatch®) supports use in wheat, faba beans, field peas, canola and barley. While it can be used safely in these crops, canola and especially barley have less tolerance, and therefore higher risk of crop effect.
- Positional separation of the herbicide from the crop seed is important for crop safety. Ensure a minimum planting depth of 1.5cm for canola and 3cm for other crops. IBS adds additional crop safety by removing most of the herbicide-treated soil from the planting furrow. The label specifically recommends against using disc seeding systems when used in canola or barley.
- Volatility is low. The Overwatch® label recommends a three metre buffer to non-target vegetation.
- Bleaching symptoms are extremely visual to certain sensitive species. Where application results in product leaving the treated field (for example, spray drift, movement under hazardous inversion conditions, physical particle drift on dust), visual damage to sensitive species may be observed. This should serve as a warning that any other products also being applied under the same conditions will be moving equally, just that they are often not as 'visual' in expression of their effects.
- Persistence is relatively long, increasing under anaerobic conditions. Where planting rotational crops (outside of those where registered for use) ensure that full label plant-back conditions are met, paying especial attention to the need for rainfall over summer months.

Group 14

Mode of action: Group 14 herbicides inhibit protoporphyrinogen oxidase (commonly referred to as PPO or protox). The PPO enzyme is a required step in early-stage chlorophyll production and is responsible for converting protoporphyrinogen to protoporphyrin. Disrupting this reaction ultimately leads to lipid radicals which attack and oxidise lipids and proteins, resulting in a loss of chlorophyll and carotenoids and leaky cell membranes. This allows cells and cell organelles to dry out and disintegrate.

There are six different subclasses of PPO available in Australia:

- diphenylethers contain the broadacre herbicides acifluorfen (for example, Blazer®), fomesafen (for example, Reflex®) and oxyfluorfen (for example, Goal®);
- N-phenyl-imides: flumioxazin (for example, Valor®), saflufenacil (for example, Sharpen®, Voraxor®) and trifludimoxazin (Voraxor®), plus those with little soil activity, butafenacil (B-Power®) and tiafenacil (Terrad'or®);

- oxadiazoles, for example, horticultural herbicides oxadiargyl and oxadiazon;
- phenylpyrazoles, for example, pyraflufen (Ecopar®); and
- triazolinones, for example, carfentrazone (Affinity®).

Despite many years of commercial use in Australia, no resistance has been reported to date. This may be partially due to these herbicides most commonly being used as a secondary herbicide in a tank mix with another mode of action. Internationally, resistance has been reported in both grass and broadleaf weeds, particularly from frequent use in soybean crops.

Several PPO inhibitors have short soil activity, however for some herbicides residual activity can be achieved at high application rates.

Diphenylethers

Oxyfluorfen					
Getting to the soil			When in the soil		
Solubility (mg/L)	0.1	Low	Binding (K _{oc})	2891–13,711 (av. 7566) (k _{loc})	Non-mobile
Vapour pressure (mPa)	0.026	Non-volatile	Half-life (DT ₅₀)	31–172 (av. 73)	Moderately persistent
Photodegradation	May contribute to dissipation from dry soils if not incorporated.		Mobility	Immobile in most soils (slightly mobile on extremely sandy soils)	
Breakdown	Moderately persistent. Microbial degradation is slow.				

Practical considerations:

- Oxyfluorfen is primarily used in broadacre cropping at very low application rates (up to 18gai/ha) as a tank mix added to knockdown herbicides. This use pattern provides very little residual activity, however it increases the speed of visual symptoms on weeds present at application and increases efficacy on certain specific weeds. To achieve medium-term residual control, oxyfluorfen is registered for use in some horticultural crops at rates of 1kg ai/ha or higher.
- Oxyfluorfen is primarily active against many broadleaf weeds. Some grasses are controlled, particularly at the higher rates used in horticulture for residual control.

Fomesafen					
Getting to the soil			When in the soil		
Solubility (mg/L)	50	Moderate	Binding (K _{oc})	50	Mobile
Vapour pressure (mPa)	4 x 10 ⁻³	Non-volatile	Half-life (DT ₅₀)	59–112 (av. 86)	Moderately persistent
Photodegradation	Photodegradation may occur if not incorporated (IBS or rainfall)		Mobility	Potential for moderate mobility	
Breakdown	Microbial breakdown. Degrades faster under anaerobic conditions.				

Practical considerations:

- Moderate solubility and low K_{oc} indicates that fomesafen will be somewhat mobile in the soil, especially on lighter soils and following heavier rainfall.
- IBS provides an additional level of positional safety by moving treated soil away from the plant line, however over time and with subsequent rainfall, it is likely that herbicide will move back towards the furrow.
- The relatively long half-life suggests that careful attention should be given to labelled plant-back conditions, especially where conditions are dry during spring/summer.
- Degradation is significantly faster under anaerobic conditions.

N-phenyl-imides

Flumioxazin

Getting to the soil			When in the soil		
Solubility (mg/L)	0.8	Low	Binding (K_{oc})	889	Slightly mobile
Vapour pressure (mPa)	0.32	Non-volatile	Half-life (DT_{50})	16–20 (av. 18)	Non-persistent
Photodegradation	Stable on the soil surface.		Mobility	Limited mobility in the soil.	
Breakdown	Primarily via microbial degradation.				

Practical considerations:

- Flumioxazin use in broadacre situations was initially via low-rate knockdown applications, mixed with a knockdown herbicide, targeting increased speed of control of a range of broadleaf weeds. Under this use pattern, many rotational crops (excluding canola) can be planted immediately after application.
- Subsequent registrations of flumioxazin have added residual control of a range of broadleaf weeds when applied prior to planting of wheat (excluding durum), faba beans, field peas and chickpeas. To achieve the desired period of weed-free early crop protection, registered application rates for residual control at planting are increased four to seven-fold compared to knockdown rates, and increased rotational crop plant-back periods apply.
- When applied as a residual herbicide, the useful level of soil binding combined with low solubility will see flumioxazin remain relatively stable in the topsoil following incorporation.
- The very low solubility will mean that good soil moisture will be required to achieve adequate root uptake.

Saflufenacil

Getting to the soil			When in the soil		
Solubility (mg/L)	2100	High	Binding (K_{oc})	9–55 ^{@5}	Mobile
Vapour pressure (mPa)	4.5 x 10 ⁻¹²	Non-volatile	Half-life (DT ₅₀)	7–35 (av. 20)	Non-persistent
Photodegradation	Some photodegradation may occur if not incorporated (IBS or rainfall)		Mobility	Potential for moderate mobility	
Breakdown	Primarily microbial breakdown. Photolysis can contribute under field conditions ^{@5}				

⁹⁵ APVMA (2012).

Practical considerations:

- In Australia, at the time of publication, pre-emergent use is only claimed when in a co-formulation with trifludimoxazin.
- Very high solubility and low K_{oc} suggests that saflufenacil will be available in the soil moisture phase. The use of IBS to move herbicide-treated soil into the inter-row may provide some initial positional safety, however the herbicide is likely to disperse in the soil water following rainfall.
- There is some potential for photodegradation if left on the soil surface for extended periods without incorporation, however the high solubility will see the herbicide rapidly enter the soil following rainfall.
- Relatively fast microbial degradation requires high initial application rates to deliver the period of residual control desired.

Trifludimoxazin

Getting to the soil			When in the soil		
Solubility (mg/L)	1.8	Low	Binding (K _{oc})	436 (K _{oc})	Mobile
Vapour pressure (mPa)	1.1 x 10 ⁻⁷	Non-volatile	Half-life (DT ₅₀)	7–42 (av. 14)	Non-persistent
Photodegradation	Not available		Mobility	Low to moderate	
Breakdown	Appears to be primarily microbial degradation.				

Practical considerations:

- In Australia, trifludimoxazin is only currently available in a co-formulation with saflufenacil.
- Low solubility and low to moderate binding suggest that the majority of herbicide will remain close to position of incorporation and therefore leaching with rainfall is likely to be minimal, unless under heavy rain and lighter soil types. IBS application moving treated soil into the inter-row is likely to provide added positional selectivity to sensitive crops.
- Relatively fast microbial degradation requires high initial application rates to deliver the period of residual control desired.

Group 15

Mode of action: Herbicides within the Group 15 mode of action inhibit very long chain fatty acid (VLCFA) synthesis within the plant. This affects waxy cuticle formation which is important in preventing water loss from the cells. Cell elongation and division are also affected.

There are four subclasses of Group 15 herbicides registered in Australia, of which three are used extensively in Australian grains production:

- chloroacetamides (for example, dimethenamid-P, metazachlor, s-metolachlor);
- isoxazolines (for example, pyroxasulfone); and
- thiocarbamates (for example, prosulfocarb, tri-allate).

At present there is only very low incidence of resistance to the Group 15 mode of action in Australia.

General properties: Thiocarbamates tend to have low mobility in the soil (high K_{oc} , low solubility) and will stay relatively close to the site of application. They typically perform better with mechanical incorporation (IBS) than purely relying on rainfall and generally require good soil moisture for efficacy. When applied by IBS, the lack of soil mobility may sometimes result in weed escapes germinating in the planting furrow.

Chloroacetamides are typically mobile in the soil (high solubility, low K_{oc}) and are generally much easier to incorporate with rainfall. The downside of increased mobility is that they are likely to move into the planting furrow, which increases the risk of crop injury.

The isoxazoline herbicide pyroxasulfone falls in between these other sub-groups. Binding is low to moderate, however solubility is low which reduces soil mobility unless rainfall is excessive.

Thiocarbamates

Prosulfocarb					
Getting to the soil			When in the soil		
Solubility (mg/L)	13.2	Low	Binding (K_{oc})	1367–2339 (av. 1693) (k_{loc})	Slightly mobile
Vapour pressure (mPa)	0.79	Non-volatile	Half-life (DT_{50})	7–13 (av. 10)	Non-persistent
Photodegradation	Insignificant		Mobility	Tight binding and low solubility means herbicide will be bound at the soil surface.	
Breakdown	Rapid microbial breakdown is the primary pathway.				

Practical considerations:

- Prosulfocarb will bind moderately tightly to organic matter, leading to the possibility of tie-up on stubble if there are high levels of organic matter present at application. Binding to stubble increases the longer it stays on stubble (days) before incorporation by rainfall or planting.
- The low solubility of prosulfocarb requires soils to be moist during the period of expected weed control for optimal results.
- The short persistence of prosulfocarb requires high application rates to achieve the desired level of residual control.
- Some labels support early post-emergent applications in wheat and barley for suppression of ryegrass. Where used early post-emergent, herbicide uptake is primarily via the roots. Weeds need to be small (one to three leaf), actively growing (good soil moisture) and rainfall is required soon after application to incorporate the herbicide.

Tri-allate					
Getting to the soil			When in the soil		
Solubility (mg/L)	4.1	Low	Binding (K_{oc})	2697–3370 (av. 3034)	Slightly mobile
Vapour pressure (mPa)	12	Requires mechanical incorporation soon after application	Half-life (DT_{50})	8–205 (av.46)	Persistent
Photodegradation	Negligible		Mobility	Significant binding and low solubility means herbicide will be bound at the soil surface.	
Breakdown	Loss due to volatility can be extremely high if not incorporated, especially in warm soils. Once in the soil breakdown is via microbial degradation.				

Practical considerations:

- The majority of seedling uptake is via absorption into the coleoptile emerging through the treated soil. Although, where soil moisture is good, there is likely to be some additional uptake via herbicide in the soil water.
- Tri-allate is one of the more volatile herbicides commonly used in the Australian grain industry. Herbicide labels recommend full mechanical incorporation into moist soil within six hours of application when used in a cultivation system. Two passes (for example, cultivation or heavy harrows followed by full disturbance sowing) will provide better incorporation than a single pass. Incorporate tri-allate to a depth of 5 to 7cm.
- In a reduced tillage farming system using the knife point IBS technique for incorporation, label rates are increased (compared to rates used in a conventional tillage system) to counteract losses from volatilisation at application, increased binding to stubble and to achieve better ryegrass control.
- Low solubility means that good soil moisture is required for the period where weed control is required. Dry conditions post-application are likely to reduce weed control, especially if the soil dries out on the surface where the herbicide is bound, but is moist at depth where weeds are germinating.

Chloroacetamides

Dimethenamid-P					
Getting to the soil			When in the soil		
Solubility (mg/L)	1499	High	Binding (K_{oc})	90–474 (av. 227) (k_{loc})	Moderate mobility
Vapour pressure (mPa)	2.5	Volatile	Half-life (DT_{50})	10–20 (av. 16)	Non-persistent
Photodegradation	Little impact		Mobility	Can be high, especially on lighter soils.	
Breakdown	Microbial degradation is the primary pathway.				

Practical considerations:

- The vapour pressure of dimethenamid-P indicates that some product could be lost to the environment over time in hot, dry conditions if not incorporated. To address this and the relatively short persistence, the Australian label recommends incorporation by sowing using a knife point or narrow tyne system.
- High solubility and moderate binding on some soils indicates that dimethenamid-P could be incorporated with minimal rainfall, however it has the potential to be mobile in some soils with high rainfall.
- Low-disturbance disc seeder systems are not recommended, as the herbicide needs to be removed from the sowing furrow. High solubility could lead to the herbicide moving down the sowing slot before binding occurs, if there is moderate to heavy rainfall after sowing.
- Relatively short persistence means that high application rates are required to achieve the desired length of pre-emergent weed control. Extended rotational crop limitations are unlikely except in specific crops in the following year, due to rapid breakdown. Check the product label for specific directions.

Metazachlor					
Getting to the soil			When in the soil		
Solubility (mg/L)	450	Moderate	Binding (K _{oc})	29–73 (av. 54)	Mobile
Vapour pressure (mPa)	0.093	Non-volatile	Half-life (DT ₅₀)	3–21 (av. 7)	Non-persistent
Photodegradation	Not a major degradation route ^{@6}		Mobility	Likely to be mobile in the soil water	
Breakdown	Multi-step enzyme-driven metabolism ^{@6}				

⁶⁶ APVMA (2016).

Practical considerations:

- Solubility is moderate and binding relatively low, so herbicide will be easily washed off stubble following minimal rainfall.
- Short persistence is unlikely to cause significant crop rotation restrictions the following season.
- Metazachlor will be mobile in the water phase in the soil, potentially moving down to the seeding zone and has potential to leach further down the profile.

S-metolachlor					
Getting to the soil			When in the soil		
Solubility (mg/L)	480	Moderate	Binding (K_{oc})	112–368 (av. 200) (k_{loc})	Moderate mobility
Vapour pressure (mPa)	3.7	Volatile	Half-life (DT_{50})	4–56 (av. 23)	Non-persistent
Photodegradation	Can be significant when applied to dry soils and not incorporated		Mobility	Level of binding is influenced by organic matter and clay content.	
Breakdown	Losses from volatility are generally low; however, losses via photodegradation can be high if not incorporated. Microbial degradation is the primary route post-incorporation.				

Practical considerations:

- Photodegradation and volatilisation losses can be significant if not incorporated (mechanical or rainfall) after application. Avoid applying under hot, dry conditions if no rainfall is forecast within the next seven to 10 days and mechanical incorporation is not employed.
- The solubility of s-metolachlor implies that incorporation can be achieved without the need for large volumes of rainfall. If heavy rainfall or irrigation occurs as the first event after application, then s-metolachlor can be prone to leaching before the herbicide has bound to the soil, especially on sandy or low organic matter soils.
- Binding varies, depending upon soil type and organic matter. S-metolachlor binds more tightly to organic matter than clay and therefore can be subject to some level of tie-up in situations of heavy stubble or weeds at application. In soils with higher clay content and/or organic matter, s-metolachlor tends to bind near the surface unless subjected to large rainfall events before binding has occurred.
- In soils with low clay content or organic matter, s-metolachlor will be loosely bound and hence can move down the profile out of the zone of surface-germinating weeds. In these soils, there is also the potential for crop injury if herbicide is moved down to the germination zone of the crop, or can be lost through leaching.
- Persistence of s-metolachlor is relatively short. In Australian use patterns, cereal crops can be sown following a pre-emergent application when using low application rates. In summer crop situations, moderate length of residual control is achieved by applying significantly higher rates than used before sowing cereals.
- In sorghum, crop selectivity is improved by treating the seed with a seed safener. This leads to faster metabolism/detoxification of the herbicide by the crop.

Pyroxasulfone					
Getting to the soil			When in the soil		
Solubility (mg/L)	3.49	Low	Binding (K _{oc})	119–226 (av. 223)	Moderate mobility
Vapour pressure (mPa)	2.4 x 10 ⁻³ (@ 25°C)	Non-volatile	Half-life (DT ₅₀)	16–26 (av. 22)	Non-persistent
Photodegradation	Only minor degradation pathway		Mobility	Relatively weak binding may allow movement down the profile	
Breakdown	Primarily microbial				

Practical considerations:

- Low solubility and moderate binding require significant rainfall to wash herbicide off stubble. However heavy rainfall after application in soils with low organic matter can see herbicide moved down the profile and into contact with the germinating wheat seed which can result in crop injury.
- Low solubility means that good ongoing soil moisture is required for uptake by the germinating weeds. Dry soil conditions between application and weed emergence can result in poor control.
- Incorporation by sowing coupled with rainfall after application is typically recommended to reduce off-target herbicide movement.
- Mateno® Complete is a three-way formulation containing pyroxasulfone in addition to aclonifen and diflufenican, which can be applied either IBS or early post-emergent (EPE) in wheat (not durum) and barley. If using pre-sowing in barley, only use with a correctly set-up IBS knife point and press wheel system and ensure a planting depth of at least 3cm to minimise crop injury. When applied EPE, uptake of the pyroxasulfone is primarily through the roots, dissolved in soil moisture. Successful EPE results on grass weeds such as ryegrass require weeds to be small (up to three leaf), actively growing (good soil moisture) and rainfall soon after application to incorporate the herbicide.

Group 23

Mode of action: Despite being in use for several decades, the mode of action of Group 23 is not well understood. It is believed that these herbicides inhibit cell division (mitosis) and microtubule organisation and polymerisation.

Carbetamide is the only current Group 23 herbicide registered for use in Australia.

Predominantly emergence is prevented, however should grass weeds emerge after a pre-emergent application, symptoms appear as severe root pruning and stunting. Plant death may follow.

The 2020 label expansion of carbetamide for use in broadacre pulse crops and winter fallow means that most broadacre paddocks will have had little exposure to this mode of action to date, and hence resistance is not currently expected. However, annual ryegrass with multiple cross-resistance to several modes of action, including carbetamide, was identified in South Australia in 1982.

Carbetamide					
Getting to the soil			When in the soil		
Solubility (mg/L)	3270	High	Binding (K_{oc})	60–118 (av. 89) (k_{loc})	Mobile
Vapour pressure (mPa)	3×10^{-3}	Non-volatile	Half-life (DT_{50})	4–29 (av. 8)	Non-persistent
Photodegradation	Not expected to be significant		Mobility	High mobility in soil water	
Breakdown	Microbial degradation. Accelerated microbial degradation has been shown following multiple applications.				

Practical considerations:

- High solubility and low K_{oc} indicates that carbetamide will be mobile in soil water. Plant uptake will be primarily via herbicide dissolved in soil water.
- Photodegradation or volatilisation are not primary dissipation pathways. When used in winter fallow, carbetamide will be stable on the soil surface and relatively easily incorporated with following rainfall.
- The label for use in pulse crops recommends IBS application with a planting depth of 3 to 5cm. IBS application provides an additional level of crop safety by moving the majority of the herbicide to the inter-row and away from the planting line. However, with subsequent rainfall, it is likely that carbetamide will disperse through the soil water.
- Post-sow pre-emergent application is also supported for use in chickpea only, however only at the low application rate.
- Under conditions favouring microbial activity (warm, moist soils), degradation is expected to be relatively fast. The period of residual control is achieved by selecting higher application rate and application in late autumn/winter where microbial activity is declining due to temperature.
- Accelerated microbial degradation has been demonstrated where multiple applications have been applied to the same field. The label advises a minimum of three years between applications.

Group 27

Mode of action: Group 27 herbicides inhibit the enzyme 4-hydroxyphenylpyruvate dioxygenase (HPPD). Inhibiting HPPD ultimately prevents the formation of carotenoids, that protect chlorophyll in plants from being destroyed by sunlight. Plants appear bleached before plant death.

There are three main subclasses of HPPD inhibitors used in Australia:

- pyrazoles include the cereal post-emergent herbicide pyrasulfotole, topamezone and the rice herbicide benzofenap;

- triketones which include the post-emergent herbicide bicycloporyne and the pre-emergent herbicide mesotrione; and
- isoxazoles, for example isoxaflutole.

Group 27 chemistry was first commercialised in the early 1980s. In Australia, several of the HPPD herbicides are used for post-emergent in-crop control. Pre-emergent registrations are currently limited to the use of mesotrione and isoxaflutole.

Globally, HPPD resistance has been limited to a small number of species to date. In Australia, metabolic cross-resistance populations of wild radish have been recently confirmed.

Triketones

Mesotrione					
Getting to the soil			When in the soil		
Solubility (mg/L)	1500	High	Binding (K _{oc})	15–390 (av. 122)	Moderate mobility
Vapour pressure (mPa)	5.7 x 10 ⁻³	Non-volatile	Half-life (DT ₅₀)	3–7 (av. 5)	Non-persistent
Photodegradation	Can enhance degradation where not incorporated by rainfall		Mobility	Moderate to high	
Breakdown	Appears to be primarily microbial degradation.				

Practical considerations:

- The Australian label supports the use of mesotrione as an IBS application prior to sowing labelled cereal crops, or a split application of IBS and post-plant, pre-emergent application timing.
- High solubility and low to moderate binding would suggest that the majority of herbicide will be available in the soil moisture phase and is likely to redistribute throughout the soil profile after application, especially following heavy rain and on lighter soil types.
- For cereal crop safety, the label requires IBS application, or where a split application is applied, the majority of herbicide to be applied IBS. Cereal crops should be planted at least 2.5cm deep. Some transient damage may still occur in following weeks as crop roots move into soil with higher herbicide concentration and/or herbicide moves back into the planting line.
- Under conditions favouring microbial activity (warm, moist soils), degradation is relatively fast. The period of residual control is achieved by selecting higher application rate and use in late autumn/winter where microbial activity is declining due to temperature.

Isoxazoles

Isoxaflutole					
Getting to the soil			When in the soil		
Solubility (mg/L)	6.2	Low	Binding (K _{oc})	124–160 (av. 145)	Moderately mobile
Vapour pressure (mPa)	3.2 x 10 ⁻⁵	Non-volatile	Half-life (DT ₅₀)	0.5–2.4 (av. 1.3)	See below
Photodegradation	Stable on the soil surface. Rainfall required to incorporate into the soil		Mobility	Potential to be mobile in the soil on sandy or gravel soils	
Breakdown	Chemical hydrolysis and microbial degradation. Breakdown is faster under warmer temperatures and higher pH.				

Practical considerations:

- After application, isoxaflutole remains stable on the soil surface. Isoxaflutole has very low solubility, however following rainfall, some herbicide will dissolve and go into solution. In soil solution, isoxaflutole has a very short half-life of less than two days, being broken down to diketonitrile (DKN) which is the herbicidal active compound. DKN has a DT_{50} of eight to 30 days.
- The extended residual control comes from more herbicide dissolving after each rainfall event.
- DKN in the soil is broken down by microbial activity. Breakdown occurs faster under higher temperatures and higher soil pH.
- Crop selectivity in chickpeas results from a combination of sowing depth to provide adequate spatial separation between the herbicide and the root zone, and species tolerance that allows for rapid detoxification of the DKN. Some chickpea varieties, such as Yorker[®], are more susceptible and hence application is not recommended on this variety.
- Rotational constraints exist for some situations (refer to label). In addition to time, there is also a rainfall requirement as extended dry periods do not support isoxaflutole breakdown. The frequency and intensity of rainfall events is a major contributing factor to length of residual persistence.

Group 30

Mode of action: Cinmethylin is currently the only active ingredient within Group 30.

Cinmethylin was first discovered in the early 1980s. Historically the mode of action of cinmethylin was unclear, with the active ingredient initially being grouped in mode of action 'Z' (unknown) for several years. It was originally proposed that cinmethylin may inhibit tyrosine aminotransferase (TAT).

More recent studies propose that inhibition of fatty acid thioesterases (FAT) is the likely mode of action. FAT is located in the plastid and is required to facilitate fatty acids movement to the endoplasmic reticulum where the plants require fatty acids for further lipid biosynthesis. As a result of this study, cinmethylin has been allocated Group 30 mode of action.

It was not until 2019 that significant use in broadacre wheat production in Australia commenced following the registration of Luximax® herbicide. Due to the relatively short period since commercial release, there is not expected to be significant resistance present in Australian weed populations at this point in time.

Cinmethylin					
Getting to the soil			When in the soil		
Solubility (mg/L)	58	Moderate	Binding (K _{oc})	266–501 (av. 318) (k _{loc})	Moderate mobility
Vapour pressure (mPa)	8.1	Volatile	Half-life (DT ₅₀)	2–208 (av. 22)	Non-persistent
Photodegradation	Not expected to be significant after incorporation by sowing		Mobility	High mobility in soil water	
Breakdown	Microbial degradation. More persistent under anaerobic conditions.				

Practical considerations:

- Moderate solubility and moderate binding reduces movement in the soil, however there may be some movement especially on lighter soil types and under high soil moisture.
- For adequate crop safety, it is very important to achieve clear separation of cinmethylin and the wheat seed via the planting process. The label only supports IBS with knife points and press wheels to move treated soil away from the planting furrow, with a minimum of 3cm planting depth required.
- “Volatilization of cinmethylin from either plant or soil surfaces may be significant with maximum volatilization rates after 24 hours of 73 per cent and 89 per cent of the applied amount from soil and plant surfaces, respectively” (APVMA, 2019). This would suggest that incorporation by sowing should be undertaken promptly after application. The Australian label requires IBS within three days.
- The mode of action of cinmethylin blocks fatty acid transfer to the endoplasmic reticulum (ER). Group 15 herbicides work in the ER by blocking transformation of these fatty acids to very long chain fatty acids. Therefore, it could be expected that the combination of Group 30 and Group 15 mode of action may enhance efficacy on grass species – both weeds and grass crops. The Luximax® label recommends not to mix with either Sakura® (pyroxasulfone) or Boxer Gold® (prosulfocarb + s-metolachlor) “as increased crop damage may occur”.
- Average soil persistence is often reported as short to moderate, depending on the soil and environmental conditions. However, in some situations, persistence can be extended (especially under anaerobic conditions or where there is a lack of soil moisture in the top 15cm over summer months).

Group 32

Mode of action: Aclonifen is currently the only active ingredient from Group 32.

Aclonifen was first commercialised in 1983. It has a diphenyl ether chemical structure so initially it was proposed that the mode of action may be similar to other diphenyl ethers which inhibit protoporphyrinogen oxidase (PPO), and therefore Group 14 mode of action. However, others suggested aclonifen symptoms typically appear as 'bleaching' similar to phytoene desaturase inhibitors (Group 12), as opposed to rapid cell necrosis typical of Group 14 mode of action.

Research published in 2020 proposes that the actual mode of action inhibits solanesyl diphosphate synthase (SDS) and hence aclonifen has been allocated Group 32. SDS is a critical enzyme in plastoquinone synthesis. Inhibition of plastoquinone will disrupt both photosynthesis and carotenoid production.

Due to the relatively short period since commercial release in Australia, coupled with availability only as a three-way formulation, there is not expected to be significant resistance present in Australian weed populations at this point in time.

Aclonifen					
Getting to the soil			When in the soil		
Solubility (mg/L)	1.4	Low	Binding (K _{oc})	5318–10,612 (av. 7126) (k _{loc})	Non-mobile
Vapour pressure (mPa)	0.016	Non-volatile	Half-life (DT ₅₀)	13–195 (av. 80)	Moderately persistent
Photodegradation	Not expected		Mobility	Low	
Breakdown	Microbial degradation				

Practical considerations:

- When applied to the soil, the low solubility and very high binding would suggest that soil movement will be very low.
- Incorporation by sowing with knife points and press wheels in a zero-till system should physically position aclonifen in the same location as germinating weed seeds on the soil surface. Significant movement back into the planting furrow is unlikely. Conversely, weed seeds germinating from depth (typical where cultivation has been previously utilised) may have roots, and the coleoptile node for grasses, below the immobile herbicide band and hence uptake may be limited.
- When applied in combination with diflufenican (in Mateno® Complete) the modes of action are likely to be complementary on susceptible weeds.
- Persistence is moderate to long. Ensure good summer rainfall for adequate degradation. As aclonifen is only currently available as a three-way formulation with diflufenican and pyroxasulfone, the degradation of all three herbicides needs to be considered.
- Aclonifen also has significant foliar activity on emerged weeds.

Group O

Mode of action: Group O is reserved for herbicides where the mode of action is yet to be confirmed. Herbicides listed within Group O are diverse in their chemical structure and may have no similarities to other herbicides within this group.

Napropamide

While napropamide has been available for use in some horticultural crops in Australia since the late 1990s, use in canola was only added to the label in recent years. Historically napropamide was listed in the previous Australian mode of action classification system as a different subclass within Group K, however it currently has been moved to the 'unknown' mode of action group.

Napropamide reduces root growth in susceptible species, possibly by inhibiting cell division. When applied as a pre-emergent application, target weed species typically do not emerge. However, where individual weeds have emerged, root growth is compromised and roots may become necrotic at the tips.

Napropamide					
Getting to the soil			When in the soil		
Solubility (mg/L)	74	Moderate	Binding (K _{oc})	435–1690 (av. 839)	Slightly mobile
Vapour pressure (mPa)	0.02	Non-volatile	Half-life (DT ₅₀)	31–127 (av. 72)	Moderately persistent
Photodegradation	Important pathway if not incorporated		Mobility	Low	
Breakdown	Microbial degradation				

Practical considerations:

- Moderate solubility and significant binding suggest that movement in the soil will be reduced.
- Photodegradation can be significant if left exposed on the soil surface. "About 50% was lost by photodecomposition after 4 days on the soil surface during summer. Under winter conditions the loss was ~30% in 8 days" (Shaner, 2014). The Australian label requires shallow mechanical incorporation into the top 25mm of soil within two to four hours of application.
- Application can be made either pre or post-planting canola, providing mechanical cultivation follows. Incorporation by sowing with knife points and press wheels in a zero-till system should be expected to physically position napropamide in the same location as germinating weed seeds, while maintaining useful separation from the canola seed.
- Due to the low soil mobility, weeds germinating below the treated soil may not be adequately controlled, hence will work best in a zero-till system where weed seeds will be close to the soil surface.
- Persistence is moderate to long. Ensure good summer rainfall for adequate degradation.

Properties of pre-emergent herbicides used in Australian grain production systems

The following table lists the important properties influencing soil availability for selected pre-emergent herbicides used in Australian broadacre farming systems. By understanding these properties and how they interrelate, advisers will be better able to plan for, predict and interpret field outcomes.

Note: An example of a common trade name is given to assist in identification of the active ingredient only. As noted in the table, some active ingredients are not commercially available in Australia as a single active formulation and contain at least one other active ingredient, so the properties of this additional active ingredient will also need consideration.

Unless otherwise stated, values quoted specific to the active ingredients in the table below have been sourced from the Pesticide Properties DataBase, which can be found at sitem.herts.ac.uk/aeru/iupac/index.htm University of Hertfordshire (2006-2003). Accessed on 23 June 2023.

Table 9: Properties of selected herbicides used in Australian grains production.

(The basis of inclusion in this table are products that are used in broadacre systems that also have plant-back constraints on their label – indicating a level of residual activity).

Mode of action	Active	Common name	Solubility ¹ (mg/L @ 20°C)	Lipophilicity ³ (Log P)	Vapour pressure ² (mPa @ 20°C)	Persistence ⁴ (DT ₅₀)	Mobility in the soil ⁵ (K _{oc} unless stated)	Primary breakdown pathway ⁶
1	Diclofop-methyl	various	0.39 (low)	4.8	2.5 x 10 ⁻²	7–39 (av. 19)	20,869 (K _{oc}) (non-mobile)	Hydrolysed to diclofop acid within a few days.
		diclofop acid	122,700 (high)	1.61	3.1 x 10 ⁻⁶	25–52 (av. 35)	289 (K _{oc}) (moderate)	
	Fenoxaprop-P-ethyl	Foxtrot®	0.43 (low)	4.58	6.5 x 10 ⁻³	0.4	5419–26,200 (av. 11,354) (non-mobile)	Rapid hydrolysis to fenoxaprop acid.
		fenoxaprop-P acid	61,000 (high)	1.83	0.18	8		Microbial degradation.
	Fluazifop-P-butyl	Fusilade®	0.93 (low)	4.5	0.12	2–38 (av. 8.2)	3394 (slightly mobile)	Hydrolysis to fluazifop acid.
		fluazifop-P acid	40.5 (low)	3.18		25	106–304 (av. 205) (moderate)	Microbial degradation.
	Haloxypop-P-methyl	Verdict®	7.9 (low)	4.0	0.055	0.5	Methyl ester estimated to be non-mobile [#]	Rapid hydrolysis to haloxypop acid.
		haloxypop-P acid	375 (moderate)	0.27	4 x 10 ⁻³ @25°C	13–36 (av. 17)	42–114 (av. 66) (mobile)	Microbial degradation.
	Propaquizafop	Shogun®	0.63 (low)	4.78	4.39 x 10 ⁻⁷	Degrades rapidly to quizalofop.	347–475 (av. 411) (K _{oc}) (moderate)	Microbial degradation.
	Quizalofop-P-ethyl	Targa®	0.6 (low)	4.61	1.1 x 10 ⁻⁴	0.6–8 (av. 1.8)	1024–3078 (av. 1816) (K _{oc}) (slightly mobile)	Quizalofop acid is a primary metabolite.
		quizalofop-P acid	1000 (high)	2.22		31–39 (av. 35)	141–1791 (av. 356) (K _{oc}) (moderate)	
Cyclohexanediones	Butroxydim	Factor®	6.9 (low)	1.9	0.001	9	635 (slightly mobile)	Rapid microbial degradation.
	Clethodim	Select®	5450 (high)	4.14	2.08 x 10 ⁻³	3	23 (K _{oc}) (mobile)	Very rapid soil degradation. Major metabolite is clethodim sulfoxide. DT ₅₀ = 7 days.
	Tralkoxydim	Achieve®	6.1 (low)	2.1	3.7 x 10 ⁻⁴	1.9	35–314 (av. 120) (moderate)	Rapid microbial degradation.
Dens*	Pinoxaden	Axial®	200 (moderate)	3.2	2.0 x 10 ⁻⁴	0.6	121–852 (av. 349) (K _{oc}) (moderate)	Hydrolysis and microbial degradation.

*Phenylpyrazoles

Table 9: Properties of selected herbicides used in Australian grains production (continued).

Mode of action		Active	Common trade name	Solubility ¹ (mg/L @ 20°C)	Lipophilicity ³ (Log P)	Vapour pressure ² (mPa @ 20°C)	Persistence ⁴ (DT ₅₀)	Mobility in the soil ⁵ (K _{oc} unless stated)	Primary breakdown pathway [#]
2	Sulfonylureas	Chlorsulfuron	various	12,500 (high)	−0.99	3.07 x 10 ^{−6}	11–185 (av. 36)	36 (K _{loc}) (mobile)	Hydrolysis is the primary pathway in neutral and acidic soils. Slow microbial degradation and slow hydrolysis is the primary pathway in alkaline soils.
		Halosulfuron-methyl	Sempre®	10 (low)	−0.02	3.5 x 10 ^{−2}	14	31–199 (av. 109) (moderate)	Rapid hydrolysis and microbial degradation.
		Iodosulfuron-methyl-sodium	Hussar®	25,000 (high)	−0.7	2.6 x 10 ^{−6}	1–10 (av. 3) Metsulfuron is a primary metabolite.	1–152 (av. 45) (k _{loc}) (mobile)	Rapid hydrolysis in neutral and acidic soils. Microbial breakdown becomes dominant in neutral to alkaline soils ^{#2} .
		Mesosulfuron-methyl	Atlantis®	483 (moderate)	−0.48	1.1 x 10 ^{−5}	7–140 (av.78)	26–345 (av. 92) (mobile)	Hydrolysis, however microbial degradation appears to also be significant under low temperatures
		Metsulfuron-methyl	Ally®	2790 (high)	−1.87	1.4 x 10 ^{−8}	7–37 (av. 13)	12 (k _{loc}) (very mobile)	Rapid hydrolysis at lower soil pH. Slow microbial degradation and hydrolysis on alkaline soils
		Sulfosulfuron	Monza®	1627 (high)	−0.77	3.05 x 10 ^{−5}	29–75 (av. 45)	5–89 (av. 33) (k _{loc}) (mobile)	Hydrolysis is the primary pathway in neutral and acidic soils. Slow microbial degradation and slow hydrolysis is the primary pathway in alkaline soils
		Triasulfuron	Logran®	815 (high)	−0.59	2.1 x 10 ^{−3}	16–92 (av. 39)	60 (mobile)	Hydrolysis is the primary pathway in neutral and acidic soils. Slow microbial degradation is the primary pathway in alkaline soils
		Tribenuron-methyl	Express®	2483 (high)	0.38	5.99 x 10 ^{−6}	2–10 (av. 4)	8–91 (av. 35) (mobile)	Rapidly degraded by hydrolysis and microbes.
	Imidazolinones	Imazamox	Raptor®	626,000 (high)	−2.9	0.0133	17	12 (k _{loc}) (very mobile)	Rapid microbial degradation. Binding increases in acidic soils which increases persistence.
		Imazapic	Flame®	2230 (high)	0.39	0.01	31–410 (av. 232)	137 (moderate)	Slow microbial degradation. Binding increases in acidic soils which increases persistence.
		Imazapyr	Arsenal®	9740 (high)	0.11	0.013	25–142 [#] (av. 90 ^{#1})	125 (k _{loc}) (moderate)	Slow microbial degradation. Binding increases in soils with pH <6.5 which increases persistence.
		Imazethapyr	Spinnaker®	1400 (high)	1.49	1.33 x 10 ^{−2}	7–290 (av. 51)	52 (mobile)	Slow microbial degradation. Binding increases in soils with pH <6.5 which increases persistence.
	Triazopyrimidines	Florasulam	Paradigm® ^A	6360 (high)	−1.22	0.01	2–18 (av. 8.5)	4–54 (av.22) (mobile)	Fast microbial degradation, especially under warm, moist conditions
		Flumetsulam	Broadstrike®	5650 (high)	0.21	3.70 x 10 ^{−7}	45	28 (mobile)	Microbial degradation is the primary pathway. This occurs faster at higher pH
		Pyroxulam	Crusader®	3200 (high)	−1.01	1 x 10 ^{−4}	5–29 ^{#3} (av. 13)	8–54 (av. 33) (mobile)	Rapid microbial degradation

Table 9: Properties of selected herbicides used in Australian grains production (continued).

Mode of action		Active	Common trade name	Solubility ¹ (mg/L @ 20°C)	Lipophilicity ³ (Log P)	Vapour pressure ² (mPa @ 20°C)	Persistence ⁴ (DT ₅₀)	Mobility in the soil ⁵ (K _{oc} unless stated)	Primary breakdown pathway [#]
3	DNAs	Pendimethalin	Stomp®	0.33 (low)	5.4	3.34 (volatile)	40–187 (av. 100)	10,241–36,604 (av. 17,491) (non-mobile)	Subject to photodegradation and volatility loss if not incorporated.
		Trifluralin	Treflan®	0.22 (low)	5.27	9.5 (volatile)	35–375 (av. 170)	15,800 (non-mobile)	Slow microbial degradation in the soil, rapid under waterlogged conditions.
	Benzamides	Propyzamide	Rustler®	9 (low)	3.27	0.058	14–271 (av. 51)	548–1340 (av. 840) (slightly mobile)	Volatilisation and photodegradation can be significant without incorporation, especially under warm, dry conditions. Microbial and non-microbial dissipation occur in the soil.
4	Arylpicolinate	Halauxifen-methyl	Paradigm® ^A	1.67 ^{@4} (low)	3.76	1.5 x 10 ⁻⁵	1.5 ^{@4}	473–2659 (av. 1418) (slightly mobile)	Rapid degradation to the acid then microbial degradation ^{@4}
			halauxifen acid	3070 (high)			14 ^{@4}	34–539 (av. 173) (moderate)	Photodegradation is insignificant relative to microbial degradation.
	Phenoxy	2,4-D dimethylamine	amine 625		Rapidly dissociates to 2,4-D acid				
		2,4-D 2-ethylhexyl ester	LVE 680	0.086 [#] (low)	5.78 [#]	0.49 [#]	9 ^{@1}	53 ^{@1}	Undergoes hydrolysis to 2,4-D acid in the soil.
			2,4-D acid	569 [#] (high)	–0.82	0.009	22–38 (av. 29)	39 Absorption increases with higher OM and/or lower pH	Microbial
		MCPA dimethylamine	750 amine		Rapidly dissociates to MCPA acid				
		MCPA 2-ethylhexyl ester	LVE 570	0.5 ^{@1} (low)			7 ^{@1}	136 ^{@1}	
			MCPA acid	825 ^{@1} (high)	–0.81	0.4	13–116 (av. 25)	110 [#]	Microbial degradation is the primary loss pathway. Some leaching and minor volatilisation.
	Pyridines	Aminopyralid	Grindstone®	2480 (high)	–2.87	2.59 x 10 ⁻⁹	3–21 (av. 12)	8 (k _{loc}) (very mobile)	Amine salts rapidly dissociate to the parent acid. Moderate potential for leaching. Primarily microbial degradation
		Clopyralid	Lontrel®	7850 (high)	–2.63	1.36 [#]	2–14 (av. 8) [EU studies] 12–70 (av. 40) [US studies] [#]	3–7 (av. 5) (very mobile)	Amine salts rapidly dissociate to the parent acid. Leaching can be significant. Microbial degradation, fastest in warm, moist soils

Table 9: Properties of selected herbicides used in Australian grains production (continued).

Mode of action		Active	Common trade name	Solubility ¹ (mg/L @ 20°C)	Lipophilicity ³ (Log P)	Vapour pressure ² (mPa @ 20°C)	Persistence ⁴ (DT ₅₀)	Mobility in the soil ⁵ (K _{oc} unless stated)	Primary breakdown pathway ⁶
4	Pyridines	Fluroxypyr-meptyl	Starane®	0.136 (low)	5.04	0.01	3	19,550 (non-mobile)	Available component rapidly converts to acid form in the soil. Then microbial breakdown.
			fluroxypyr acid	6500	0.04	3.8 x 10 ⁻⁶	34–68 (av. 51) [#]	51–81 (av. 68) (k _{toc}) (mobile)	Microbial breakdown
		Picloram	Tordon®	488 (moderate)	–1.92	2 x 10 ⁻³	20–49 (av. 34) [EU studies] 20–300 (av. 90) [#] [US studies] Increases with application rate.	13 (very mobile)	Amine salts rapidly dissociate to the parent acid. Photolysis and leaching can be significant. Slow microbial degradation. Fastest under warm, moist conditions.
		Triclopyr-butoxyethyl	Garlon®	23 [#] (low)				780 [#] (slightly mobile)	Available component rapidly converts to acid form in the soil.
			triclopyr acid	435 [#] (moderate)	–0.45	0.2	10–46 [#] (av. 30)	27 (mobile)	Microbial
5	Triazines	Atrazine	Gesaprim®	35 (low)	2.7	0.039	6–108 (av. 60) [#]	89–513 (av. 100) (moderate)	Hydrolysis is the primary pathway in neutral and acidic soils. Slow microbial degradation is the primary pathway in alkaline soils.
		Cyanazine	Bladex®	171 (moderate)	2.1	2.13 x 10 ⁻⁴	12–25 (av. 16)	190 (moderate)	Microbial degradation is the primary degradation pathway. Hydrolysis also occurs rapidly in acidic soils.
		Prometryn	Gesagard®	33 (low)	3.34	0.13	41	400 (moderate)	Microbial
		Simazine	Gesatop®	5 (low)	2.3	8.1 x 10 ⁻⁴	27–102 (av. 90)	130 (moderate)	Hydrolysis is the primary pathway in neutral and acidic soils. Slow microbial degradation is the primary pathway in alkaline soils.
		Terbutylazine	Terbyne®	7 (low)	3.4	0.152	16–149 (av. 22)	231 (k _{toc}) (moderate)	Hydrolysis is the primary pathway in neutral and acidic soils. Slow microbial degradation is the primary pathway in alkaline soils.
	Triazinones	Metribuzin	Sencor®	1100 [#] (high)	1.75	0.121	14–28 [#] (av. 19) 30–60 under cool dry conditions [#]	27–82 (av. 48) (k _{toc}) (mobile)	Microbial
	Ureas	Diuron	diuron	36 (low)	2.87	1.15 x 10 ⁻³	54–792 (av. 229)	238–1750 (av. 680) (slightly mobile)	Volatilisation and photodegradation losses are typically low, but can be significant under hot and dry conditions if not incorporated. Slow microbial degradation in the soil.
		Fluometuron	Cotoran®	111 (moderate)	2.28	0.125	63–117 (av. 90)	31–117 (av. 67) (k _{toc}) (moderate)	Photodegradation is significant, especially under dry conditions. Slow microbial metabolism in the soil.
	12	pyridinecarboxamide	Diflufenican	Brodal®	0.05 (low)	4.2	4.25 x 10 ⁻³	105–210 [#]	1622–2369 [#] (slightly mobile)
Picolinafen			Sniper®	0.047 (low)	5.43	1.7 x 10 ⁻⁴	9–64 (av. 31)	28,300 (non-mobile)	Mineralisation to CO ₂ and two primary metabolites.

Table 9: Properties of selected herbicides used in Australian grains production (continued).

Mode of action		Active	Common trade name	Solubility ¹ (mg/L @ 20°C)	Lipophilicity ³ (Log P)	Vapour pressure ² (mPa @ 20°C)	Persistence ⁴ (DT ₅₀)	Mobility in the soil ⁵ (K _{oc} unless stated)	Primary breakdown pathway [#]
13	Isoxazolidinones	Bixlozone	Overwatch®	40 (low)	3.3	1.1	11–245 (av. 99)	315–541 (k _{loc}) (moderate)	Microbial. Very persistent under anaerobic conditions.
14	Diphenylether	Fomesafen	Reflex®	50 (moderate)	–1.2	4 x 10 ^{–3}	59–112 (av. 86)	50 (mobile)	Microbial. Degrades faster under anaerobic conditions.
		Oxyfluorfen	Goal®	0.1 (low)	4.86	0.026	31–172 (av. 73)	2891–13,711 (av. 7566) (k _{loc}) (non-mobile)	Photolysis is important. Microbial breakdown is slow.
	N-phenyl-imides	Flumioxazin	Valor®	0.8 (low)	2.55	0.32	16–20 (av. 18)	889 (slightly mobile)	Microbial
		Saflufenacil	Sharpen®	2100 (high)	2.6	4.5 x 10 ^{–12}	7–35 (av. 20)	9–55 ^{#5} (mobile)	Primarily microbial. Photolysis can contribute under field conditions. ^{#5}
		Trifludimoxazin	Voraxor® ^B	1.8 (low)	3.33	1.1 x 10 ^{–7}	7–42 (av. 14)	436 (K _{loc}) (moderate)	Microbial
15	Thiocarbamates	Prosulfocarb	Arcade®	13.2 (low)	4.48	0.79	7–13 (av. 10)	1367–2339 (av. 1693) (k _{loc}) (slightly mobile)	Microbial
		Tri-allate	Avadex®	4.1 (low)	4.06	12	8–205 (av. 46)	2697–3370 (av. 3034) (slightly mobile)	Volatilisation and microbial
	Chloroacetamides	Dimethenamid-P	Outlook®	1499 (high)	1.89	2.5	10–20 (av. 16)	90–474 (av. 227) (k _{loc}) (moderate)	Microbial
		Metazachlor	Butisan®	450 (moderate)	2.49	0.093	3–21 (av. 7)	29–73 (av. 54) (mobile)	Multi-step enzyme driven metabolism ^{#6}
		S-metolachlor	Dual®	480 (moderate)	3.05	3.7	4–56 (av. 23)	112–368 (av. 200) (k _{loc}) (moderate)	Volatility generally low but photodegradation can be high prior to incorporation. Microbial degradation.
	Isoxazolinones	Pyroxasulfone	Sakura®	3.49 (low)	2.39	2.4 X 10 ^{–3} @ 25°C	16–26 (av. 22)	119–226 (av. 223) (moderate)	Microbial via cleavage of the methyl-sulfone bridge ^{#7}
23	Carbamates	Carbetamide	Ulto®	3270 (high)	1.78	3 x 10 ^{–3}	4–29 (av. 8)	60–118 (av. 89) (k _{loc}) (moderate)	Microbial
27	Pyrazole	Pyrasulfotole	Precept® ^C	69,100 (high)	–1.36	2.7 x 10 ^{–4}	16–87 (av. 55)	22–715 (av. 368) (moderate)	Microbial
		Topramezone	Frequency®	100,000 (high)	–1.52	1.1 x 10 ^{–9}	11–69 (av. 26)	38–303 (av. 171) (moderate)	Microbial
	Triketone	Bicyclopyrone	Talinor® ^D	119,000 @ 25°C ^{#8} (high)	–1.2	5 x 10 ^{–8}	2–36 ^{#8}	6–50 in most soils ^{#8} (very mobile)	Photolysis appears significant under field conditions ^{#8}
		Mesotrione	Callisto®	1500 (high)	0.11	5.7 x 10 ^{–3}	3–7 (av. 5)	15–390 (av. 122) (moderate)	Microbial
	Isoxazole	Isoxaflutole	Balance®	6.2 (low)	2.34	3.22 x 10 ^{–5}	0.5–2.4 (av. 1.3)	124–160 (av. 145) (moderate)	Rapid chemical hydrolysis to the active metabolite
			diketetonitrile metabolite	22,660	–0.4	2.6 x 10 ^{–4}	8–30 ^{#9} (av. 9)	11–99 (av. 35) (k _{loc}) (mobile)	Microbial degradation
29	Benzamides	Isoxaben	Gallery®	0.93 (low)	3.94	2 x 10 ^{–4}	66–309 (av. 123)	700–1290 (av. 909) (slightly mobile)	Microbial
30	Cineoles	Cinmethylin	Luximax®	58 (moderate)	4.5	8.1	2–208 (av 22)	266–510 (av. 318) (k _{loc}) (moderate)	Microbial. More persistent under anaerobic conditions.

Table 9: Properties of selected herbicides used in Australian grains production (continued).

Mode of action	Active	Common trade name	Solubility ¹ (mg/L @ 20°C)	Lipophilicity ³ (Log P)	Vapour pressure ² (mPa @ 20°C)	Persistence ⁴ (DT ₅₀)	Mobility in the soil ⁵ (K _{oc} unless stated)	Primary breakdown pathway [#]
32 Diphenyl ether	Aclonifen	Mateno [®] Complete ^E	1.4 (low)	4.37	0.016	13–195 (av. 80)	5318–10,612 (av. 7126) (K _{10c}) (non-mobile)	Microbial
0 Acetamides	Napropamide	Devrinol ^{®C}	74 (moderate)	3.3	0.02	31–127 (av. 72)	435–1690 (av. 839) (slightly mobile)	Microbial. Photodegradation is important if not incorporated.

Unless otherwise stated, information in this table is sourced from the Pesticide Properties DataBase which can be found at sitem.herts.ac.uk/aeru/iupac/index.htm

The Pesticide Properties DataBase (PPDB) developed by the Agriculture & Environment Research Unit (AERU), University of Hertfordshire, 2006–2023.

Accessed on 27 June 2023.

¹ Solubility in water (mg/L @ 20°C) (rating)

² Vapour pressure (mPa @ 20°C)

³ Octanol-water partition coefficient (Log P)

⁴ Persistence measured as average DT₅₀ (days for 50% decomposition) under field situations

⁵ Mobility in the soil – propensity for soil binding using average K_{oc} or K_{10c} value to determine rating

[#] Shaner (2014) Herbicide Handbook. Weed Society of America

^{®1} USDA Natural Resources Conservation Service (n.d.) Windows Pesticide Screening Tool

^{®2} Bayer CropScience (2014) Hussar OD 2014 plant-back guide

^{®3} APVMA (2008) Evaluation of the new active pyroxsulam in the product Crusader Herbicide

^{®4} Dow AgroSciences (2013) Arylex[®] active technical bulletin

^{®5} APVMA (2012) Evaluation of the new active saflufenacil in the product Sharpen WG Herbicide

^{®6} APVMA (2016) Evaluation of the new active metazachlor in the product Butisan Herbicide

^{®7} APVMA (2011) Evaluation of the new active pyroxasulfone in the Product Sakura[®] 850 WG Herbicide

^{®8} APVMA (2017) Evaluation of the new active bicyclopyrone in the product Talinor Herbicide

^{®9} Bayer CropScience (2011) Balance[®] Herbicide technical guide

^A Paradigm[®] is a mixture of florasulam and halauxifen-methyl

^B Voraxor[®] is a mixture of saflufenacil and trifludimoxazin

^C Precept[®] is a mixture of pyrasulfotole and MCPA

^D Talinor[®] is a mixture of bicyclopyrone and bromoxynil

^E Mateno[®] Complete is a mixture of aclonifen, pyroxasulfone and diflufenican

Further information

Re-cropping periods for NSW

Fleming J, McNee T, Cook T and Manning B (2012) *Weed control in summer crops 2012-13*, NSW Department of Primary Industries.
dpi.nsw.gov.au/__data/assets/pdf_file/0008/248471/Weed-control-in-summer-crops-2012-13.pdf

Heuston P and Macpherson M (2023) *Weed control in winter crops 2023*, NSW Department of Primary Industries.
dpi.nsw.gov.au/__data/assets/pdf_file/0006/1465890/Weed-control-in-winter-crops-2023.pdf

Videos

GRDC: Pre-emergent Herbicides – Part 1 Solubility & Binding
youtube.com/watch?v=s63GYYflzw&t=1s

GRDC: Pre-emergent Herbicides – Part 2 Incorporation by Sowing
youtube.com/watch?v=LJNjuMWS57U&t=1s

Online learning

WeedSmart Learning Hub: Pre-emergent Herbicides 101
learninghub.weedsmart.org.au/courses/pre-emergent-herbicides-101

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