Integrated weed management in arable crop systems

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1. Introduction

This report was commissioned by the Foundation for Arable Research as part of the MBIE funded 'Managing herbicide resistance' national project. The aim is to release it as extension material to arable farmers.

The increasing numbers of herbicide resistant (HR) weeds coupled with the growing range of challenges in agriculture and horticulture, such as nutrient loss to water, mitigation and adaptation to the climate crisis mean that a significant shift in weed management is imperative. This handbook provides a guide to that weed management shift: both fundamentals and especially practical options. The key message is we need to shift from herbicide based weed management systems to much more diversified integrated weed management systems.

1.1. What is integrated weed management?

Integrated weed management (IWM) is where all possible weed management tools are used in a purposefully combined / integrated system to achieve excellent weed management. It is divided up into four main approaches: physical, chemical, biological and ecological that can be considered the four toolboxes of IWM (Figure 1).

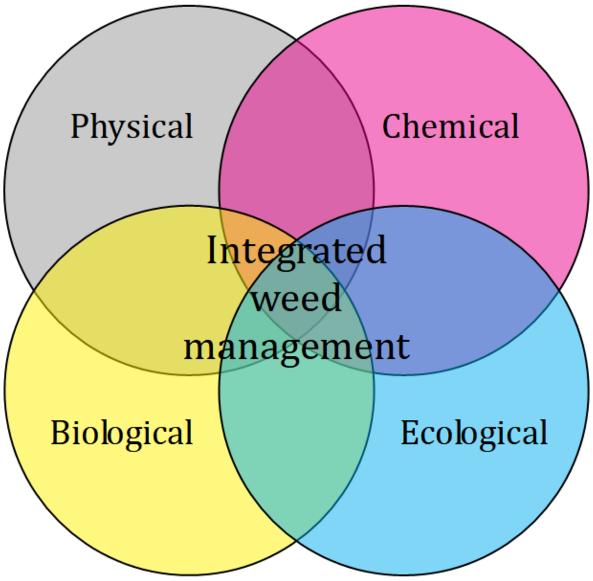


Figure 1. Combining the physical, chemical, biological and ecological toolboxes to form integrated weed management (IWM).

Physical tools are mostly mechanical approaches, such as interrow hoes and cultivation. Chemical tools are principally herbicides. Biological and ecological tools overlap, and are also called cultural tools. They are based on biological and ecological interactions among the living things in a paddock, for example biocontrol agents, competition between the crop and weeds and rotations. The four toolboxes are not supposed to be hard and fast, as some tools can belong in more than one toolbox, rather, the aim is to emphasise the diversity of tools.

Another useful metaphor is "Many little hammers" [12] where a combination of weeding tools that would not achieve acceptable weed control by themselves, when combined, can achieve cumulative even synergistic weed management outcomes. An additional advantage is that if one little hammer fails, the other hammers can compensate. This compares with the 'sledge hammer' of herbicides, where, the entire weed management strategy is dependent on small number of applications of one or a few herbicides. If one of these applications fail, then, control of weeds in that crop may fail completely.

The corollary of many little hammers is that diversity is king. Diversity of crops, diversity of herbicides, diversity of rotations, diversity of thought, etc. If there is a key point for managing herbicide resistance, it is: diversity, diversity, diversity. Monoculture is the sure fire path to resistance.

1.2. What is a weed?

After 70+ years of weed science it could be expected that the definition of a weed would be settled. That it is not, is because the concept of weeds is not a scientific or biological one, it is a value judgement about a particular plants value or lack of value. IWM requires a re-evaluation of what is considered a weed. With the advent of herbicides many plants that had not been considered weeds, often because it was not worth the cost of controlling them, were re-classed as weeds because the effectiveness and reliability of herbicides meant killing them was now and easy and cheap. This resulted in the view that all non-crop plants were therefore weeds, and that individual plant species came to be declared weeds regardless of where they were growing. However, weed management is fundamentally a cost-benefit exercise: the increased returns from weed control need to be larger than the cost of control - based on a long-term perspective due to the weed seed bank. As the cost of weed management changes, therefore, the decision about whether a plant is a weed or not, also changes.

Among the many definition of weeds, 'a plant growing where it is not wanted' sums up most of them. However, taking a cost-benefit perspective, a weed is a plant that will cause an economic loss. This can be in both the short term, e.g. competing with crop plants, and long term, e.g. setting seeds such that future populations of weeds are more costly to control. However, if the economic loss (short and long term) is smaller than the cost of control, then, controlling the weeds will increase the economic loss, therefore, simply declaring the plant to be 'not a weed' is the economically rational thing to do. Weeds can therefore be considered to be:

"A plant, or population of plants, at a given time and place,
that would cause an economic loss, greater than the cost of control,
over both the short and long term"

Therefore, instead of there being two classes of plants in a paddock: crop and weeds, there are now three classes:

- Crop;
- Non-crop plants;
- Weeds.

Non-crop plants are therefore plants whose economic cost is smaller than the cost of control, and therefore it is unprofitable to control them. This analysis also means that a particular plant species may be a weed in one paddock/crop in one year, but not in another paddock/crop in another year. This abolishes the idea that a particular plant species is a weed, wherever and whenever it is growing.

1.3. Beyond direct cost-benefit analysis of weeds

There are also wider issues beyond the direct cost-benefit analysis for a given crop, in that non-crop plants can provide valuable 'ecosystem services'[1] such as providing nectar and pollen to beneficial insects that help control crop pests, so non-crop plants and weeds have positive as well as negative values. Many weed control tools can have economic externalities, for example, impacts on soil health from hoeing, or, herbicides getting into waterways and impacting ecosystems. There are also the impacts on the long-term viability of different tools, for example, over-reliance on a restricted range of herbicides can result in resistance developing so the herbicides no longer work. It is therefore vital to also consider such wider issues when considering weed management options and deciding what are weeds and what are non-crop plants.

IWM therefore brings these wider issues into consideration with the aim of creating effective, economically rational, weed management systems that will last for the long-term.

[1] wikipedia.org/wiki/Ecosystem_services

2. Herbicide resistance: the global and NZ state of play

The Weed Science Society of America (WSSA) defines herbicide resistance as

> "The inherited ability of a plant to survive and reproduce following exposure to a dose of herbicide normally lethal to the wild type. In a plant, resistance may be naturally occurring or induced by such techniques as genetic engineering or selection of variants produced by tissue culture or mutagenesis."

This compares with herbicide tolerance which is defined as

> "The inherent ability of a species to survive and reproduce after herbicide treatment. This implies that there was no selection or genetic manipulation to make the plant tolerant; it is naturally tolerant."

Herbicide resistance (HR) is therefore the result of evolution, a species of plant that used to be killed by a herbicide is no longer killed, and, the ability to survive herbicide application is genetically passed onto the plants progeny. Tolerance is where a herbicide never killed a plant species in the first place, e.g., crops tolerant of a selective herbicide. Tolerance does not mean the herbicide has no effect at all, it may cause temporary harm (even significant harm) to the plant, but the herbicide will not kill it.

The first case (plant species × herbicide mode of action) of a HR plant occurred in the 1950s, which is the same time that herbicides use became widespread. By the start of the 1980s there were only nine cases of resistance, but since then the number of resistant cases has increased linearly at approx. 120 cases a decade with no sign of leveling off (Figure 1).

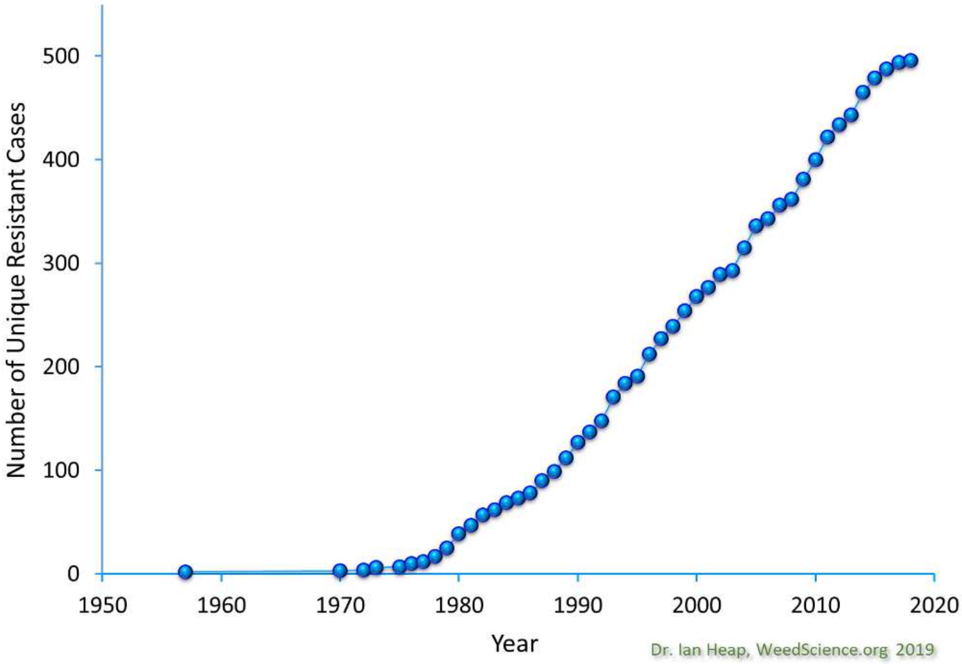


Figure 2. Global increase in unique herbicide resistant cases (plant species × herbicide mode of action). From weedscience.org.

So, while there has not been a change in the rate of increase in HR cases over four decades, the number of cases that have built up, now, means that HR is impacting nearly all cropping systems globally.

2.1. The global herbicide resistance situation

The website weedscience.org is a compendium of the current, global HR data. As of October 2019, there are 505 unique cases (species × herbicide mode of action) of HR plants globally, with 259 species - 151 dicots and 108 monocots. Plants have evolved resistance to 23 of the 26 known herbicide modes of action and to 167 different herbicides. Resistance is spread among a wide range of plant families:

including grasses 82 species, Asteraceae (sunflower family) 42, brassicas 22, sedges 12, amaranths 11, figworts 9, knotweeds 8, water-plantains 7, Chenopodioideae (fat hen family) 7, and carnations 6.

Figure 3 shows the growth in the number of plant species resistant to a range of modes of action (MoA), with the ALS inhibitors (Group B, sulfonylureas, imidazolinones and triazolopyrimidines) and PSII inhibitors (Group C 1-3, triazines, triazines, uracils, pyridazinones, phenyl-carbamates, ureas, nitriles, benzothiadiazinone, and phenyl-pyridazines) being the MoA with the largest number of resistant plant species. See Table 7 for MoA details and examples of product names.

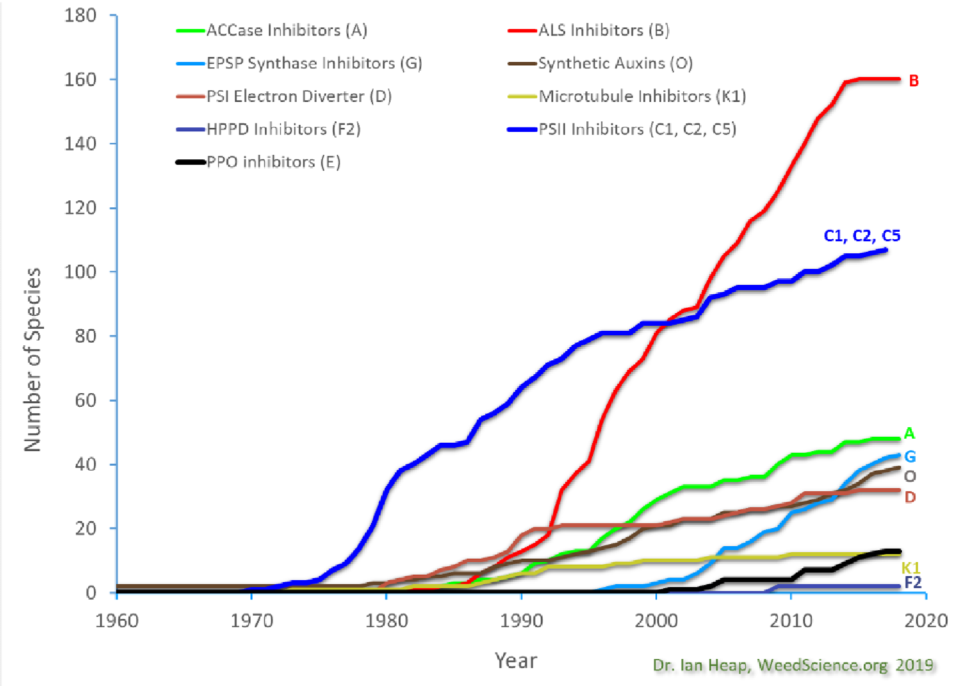


Figure 3. The increase in number of plant species resistant to a range of herbicide modes of action. From weedscience.org.

Figure 4 shows the plant species resistant to the most modes of action globally, note the top six are all grasses.

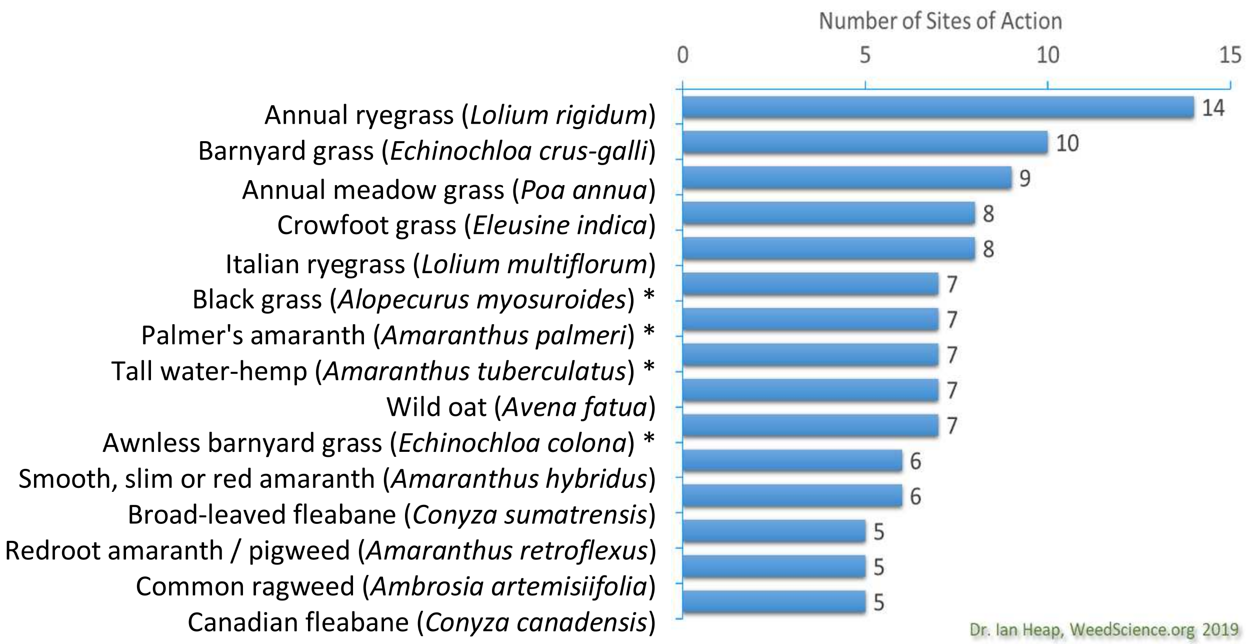


Figure 4. Species of plant resistant to multiple modes (sites) of action, globally. Species with an '*' are not present in NZ. From weedscience.org.

Figure 5 shows the global increase in glyphosate resistant plants, also with a wide representation from different plant families.

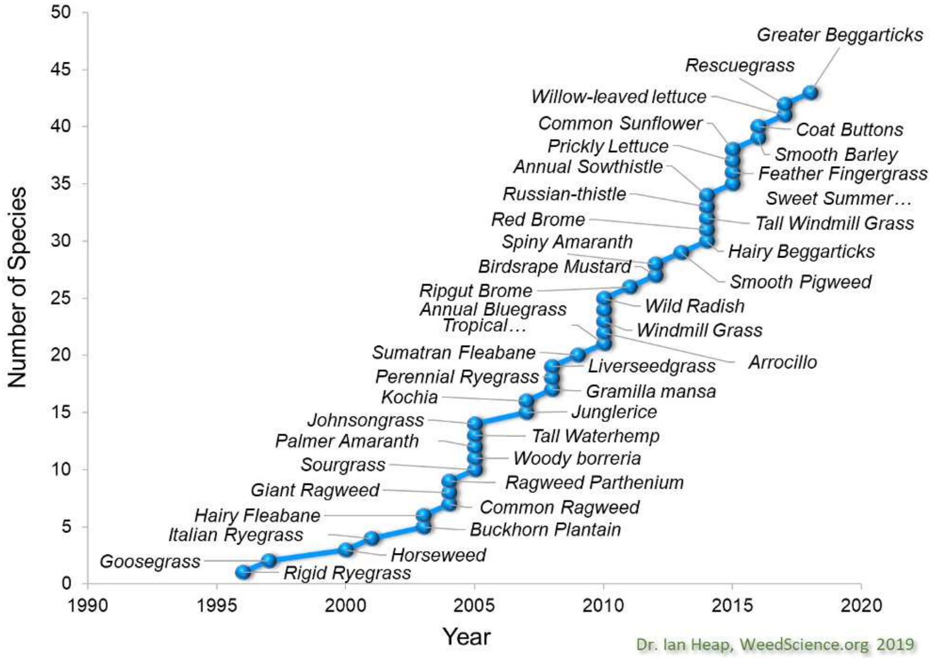


Figure 5. Increase in glyphosate resistant plants globally. From weedscience.org.

The message from the above is crystal clear:

- The number of HR plants is increasing continually with no sign of slowing down.
- The species of HR plants are spread through many plant families, showing that any plant species can develop resistance.
- At the same time, the grasses and the sunflower families are over-represented in the number of species that are resistant, and, for the grasses, the number of species with resistance to multiple modes of action (Figure 4).
- That not all modes of action are equally susceptible to plants developing resistance (Figure 3).
- Glyphosate (EPSP synthase inhibitors) is a close fourth in the number of plants with resistance to it (Figure 3) and those plants are spread across many plant families (Figure 5) showing it is not just a small range of plant species that have developed resistance to glyphosate.

2.2. No new herbicide chemistry

While the number of HR plant species continues to increase, the same is not true of new herbicide chemistry. The last novel MoA was the ALS herbicides introduced in the 1980s, and no new herbicide MoA has been introduced since. There is a 'discovery dilemma': a long residual life, good soil mobility and activity in soil are desirable for weed control but a short residual life, low water solubility and high soil absorbtion are desirable environmentally, hence it is very difficult to find new active ingredients that perform well in both areas [25]. Despite this agrichemical companies are still working to discover new MoA, although if new products are put on the market, it is vital that they are used in an IWM framework to maximise their effective lifespan before resistance develops, i.e., shifting to IWM is essential even if new MoAs are discovered.

2.3. Herbicide resistance in New Zealand

In New Zealand the number of positively identified HR plants is 19 with the first identified in 1979 with a linear increase over the last four decades (Table 1).

Table 1. New Zealand herbicide resistant cases (species × mode of action) in order of discovery, as of October 2019. From weedscience.org.

#	Species	Common Name	Year	Mode of Action	MoA Code
1	*Chenopodium album*	Fat hen	1979	Photosystem II inhibitors	C1
2	*Polygonum persicaria*	Willow weed	1980	Photosystem II inhibitors	C1
3	*Carduus nutans*	Nodding thistle	1981	Synthetic Auxins	O
4	*Ranunculus acris*	Giant buttercup	1988	Synthetic Auxins	O
5	*Nassella neesiana*	Chilean needlegrass	1992	Lipid Inhibitors	N
6	*Stellaria media*	Common chickweed	1995	ALS inhibitors	B
7	*Carduus pycnocephalus*	Slender winged thistle	1997	Synthetic Auxins	O
8	*Solanum nigrum*	Black nightshade	1999	Photosystem II inhibitors	C1
9	*Soliva sessilis*	Onehunga weed	1999	Synthetic Auxins	O
10	*Chenopodium album*	Fat hen	2005	Synthetic Auxins	O
11	*Solanum americanum*	Small-flowered nightshade	2009	PSI Electron Diverter	D
12	*Solanum nigrum*	Black nightshade	2009	PSI Electron Diverter	D
13	*Ranunculus acris*	Giant buttercup	2010	ALS inhibitors	B
14	*Ranunculus acris*	Giant buttercup	2010	Multiple Resistance: 2 Sites of Action ALS inhibitors Synthetic Auxins	B O
15	*Lolium perenne* ssp. *multiflorum*	Italian ryegrass	2012	EPSP synthase inhibitors	G
16	*Lolium perenne*	Perennial ryegrass	2012	EPSP synthase inhibitors	G
17	*Avena fatua*	Wild oat	2014	ACCase inhibitors	A
18	*Lolium perenne*	Perennial ryegrass	2015	Multiple Resistance: 3 Sites of Action Carotenoid biosynthesis (unknown target) EPSP synthase inhibitors Glutamine synthase inhibitors	F3 G H
19	*Lolium perenne ssp. multiflorum*	Italian ryegrass	2015	Multiple Resistance: 3 Sites of Action Carotenoid biosynthesis (unknown target) EPSP synthase inhibitors Glutamine synthase inhibitors	F3 G H

While the number of resistant plants in New Zealand is considerably lower than in other countries, the overall situation is similar, in that the numbers are increasing linearly, a range of plant families have developed resistance, with the grasses having the highest representation, there are plants with resistance to multiple MoAs (three species), and a range of MoAs are effected (Table 2).

Table 2. The number of plant species in New Zealand, resistant to different herbicide modes of action, as of October 2019. Summarised from Table 1.

No, resistant plant species	Mode of Action (MoA)	MoA Code	Example Active Ingredients
6	Synthetic Auxins	O	2,4-D, aminopyralid, dicamba
4	EPSP synthase inhibitors	G	Glyphosate
3	ALS inhibitors	B	Metsulfuron-methyl, thifensulfuron-methyl
3	Photosystem II inhibitors	C1	Terbuthylazine, atrazine, hexazinone
2	Carotenoid biosynthesis	F3	Amitrole, clomazone
2	Glutamine synthase inhibitors	H	Glufosinate-ammonium
2	PSI Electron Diverter	D	Diquat, paraquat
1	ACCase inhibitors	A	Fenoxaprop-P-ethyl, haloxyfop-P, clethodim
1	Lipid Inhibitors	N	Prosulfocarb, ethofumesate, flupropanate

2.3.1. New Zealand: a world leader in herbicide resistant plants?

While NZ has a considerably lower absolute number of HR plants than countries such as the USA and Australia, those countries have a much larger area of cropped land. Table 3 shows the top five countries with the highest number of HR plants, New Zealand ranks 17th with 20 HR plants. In comparison, Table 4 shows the number of km^2 of 'cultivated land' (arable + permanant crops) for each HR plant, New Zealand now ranks second, the USA now ranks 40th and Australia 30th. This ranking should not be considered absolute, as many other factors influence the result, primarily how many resources have been put into finding HR plants, but, it clearly illustrates that HR plants are as a substantial issue, if not more, for New Zealand as countries such as the USA and Australia.

Table 3. Top five countries with the highest absolute number of herbicide resistant cases (plant sp. × MoA). From weedscience.org.

Rank	Country	No. HR cases
1	United States	164
2	Australia	92
3	Canada	68
4	France	52
5	Brazil	48

Table 4. Top five countries with the highest number of herbicide resistant cases (plant sp. × MoA) per km^2 of cropping land (arable + permanant crops). Based on [a] weedscience.org and [b] Wikipedia.

Rank	Country	No. HR cases[a]	Cultivated area km^2 [b]	Cultivated area km^2 per HR cases
1	Israel	37	3,640	98
2	New Zealand	20	5,642	282
3	Switzerland	15	4,461	297
4	Belgium	22	8,540	388
5	Cyprus	2	1,206	603

2.4. Evolved resistance does not just apply to herbicides

Evolved resistance is most commonly associated with the agrichemicals, however, evolution can evolve 'resistance' to any 'static' control measure, i.e., a control measure that is not evolving or changing itself. For example harvest weed seed control systems where weed seeds harvested along with cereal grain by headers / combine harvester are destroyed, rather than being returned to the soil, has resulted in weeds where the seed heads shatter more easily so seeds are released when cut by the sickle bar, falling on the soil rather than entering the header / combine. Control of the Argentine stem weevil

(ASW) by the parasitoid wasp *Miroctonus hyperodae*, is failing even though this is a biological control approach, because ASW reproduces sexually and is evolving while *Miroctonus* reproduces asexually, so it is not evolving, i.e., it is a 'static' control. These examples illustrate why it is vital to take IWM approach and use as many, widely differing, tools as possible, to avoid, not only resistance to chemicals, but, resistance to any, non-evolving tool occurring.

2.5. Herbicide resistance conclusions

The overall message is that while New Zealand does not have the large absolute numbers of resistant plant species than countries such as Australia and the USA have, the number of HR plants for our cropped land area is very large, and therefore of considerable concern. The lessons from overseas is that it will get worse still, unless we are proactive in addressing the problem.

The key purpose of this booklet is therefore to maximise the use of IWM to minimise the evolution of new HR plants, so that the herbicides will keep working for as long as possible. The loss of any herbicide against any plant species is a vicious cycle: as it is highly unlikely any new MoA will be introduced, so as each herbicide is lost, the, remaining herbicide options reduce, which increases the likelihood of resistance developing even faster to the remaining herbicides, i.e., a vicious cycle. Therefore to maximise the effective lifespan of herbicides we need to minimise their use and substitute non-chemical options as much as possible. If herbicides continue to dominate weed management, then, their effectiveness will rapidly decline such that non-chemical methods will be the only one available, without any recourse to herbicides in situations where non-chemical control is much more difficult.

3. The foundations of integrated weed management (IWM)

Herbicide (chemical) based weed management views weeds through the lens of their biochemistry: is a plant tolerant or susceptible to a particular herbicide chemistry? In IWM we also need to look at weeds through the lenses of physics, biology and ecology to create a full understanding of the weed (section 1.1). An analogy: herbicides are like a military tank, very powerful but with one tactic; IWM is more akin to the martial arts, you study your opponents strengths and weaknesses, and then target their weaknesses, to defeat them. This section therefore describes the core knowledge required in IWM to identify weeds weaknesses and how to target them.

3.1. The weed seed bank

The heart of IWM in cropping systems is the management of the weed seedbank. This is because the vast majority of weeds are annuals plus a few biannuals and the evolutionary strategy of these plants / weeds is to 'be a seed'. Such plants are called therophytes as the seed is the permanant life stage that survives unfavourable seasons, and, is the longest lived part of the life cycle (years, decades, even a century). In comparison, the therophyte weed plant is ephemeral, growing for a few weeks to two seasons (biannuals), before, it produces seed and must die. For perennial plants their evolutionary strategy is exactly the opposite: their permanant life stage is the plant, which can survive for centuries (e.g., trees), while the seeds are ephemeral, remaining viable for only a few months or few years. So, just as it makes no sense to try to control perennial weeds by targeting their ephemeral seeds, only targeting the ephemeral life stage of the therophytes, i.e., the plant, is not controlling their fundamental life stage, i.e., their seeds. Thus the focus in IWM shifts from controlling weed plants in the crop to managing the weed seedbank.

3.1.1. Seed dispersal

Due to the many impressive means plants have evolved to disperse their seeds, there is a belief that weed seeds in cropping systems are dispersed widely and there is considerable paddock-to-paddock and farm-to-farm traffic. In reality, in cropping systems, even for those species with highly effective dispersal systems, e.g., thistles, most shed seeds fall within a few meters of the parent plant. Therefore the current weed seedbank in a paddock has come almost entirely from the previous generations of weeds seeding in that same paddock.

The small amount of seed that does move between paddocks and farms, mostly via machinery, while insignificant in terms of the seedbanks already present, can be really critical in terms of bringing in weed species that are not already present, and, bringing in seeds from HR weeds. Minimising the amount of weed seed brought onto a property by practicing good hygiene can therefore be critical for keeping HR and novel weeds from establishing on your property.

3.1.2. Broadleaf vs. grass seeds: tough vs. soft

Most broadleaf (dicotyledonous) plants have seeds with a tough seed coat that allows them to survive in the soil for decades. In contrast most grass (monocotyledonous) plants lack the tough seed coat of broadleafs so the seed typically lasts a maximum of seven years buried in soil before it dies. The term 'hard seed' refers to broadleaf seeds that have an extra tough / thick seed coat that enforces dormancy by physically blocking water and oxygen reaching the seed embryo, and until that seed coat has been degraded the seed is unable to germinate. Both crops and weeds exhibit hard seed, often with individual plants producing both normal and hard seed, so that if immediate conditions are good for germination the normal / non-hard seed will germinate, but, the hard seed will not, and is forced to wait until future years, thereby increasing the overall chances of the species survival.

3.1.3. Prevention and depletion of the weed seedbank

The weed seedbank is managed thought prevention and depletion. The old farming adage 'One years seeding: seven years weeding' speaks to the fact that it is easier to control weeds by preventing weed seeds entering the seedbank (weed seed rain) than it is to control the subsequent weed plants that emerge from the seedbank. The harvest weed seed control (HWSC) systems, such as the Harrington Seed Destructor, clearly shows the potential of controlling the weed seed rain, with a reduction in annual ryegrass emergence by 90% achieved in four years [26]. A USA study found that preventing weed seed rain reduced subsequent years weed seedbanks compared with other autumn treatments between 45% and 93% and weed seedling densities by 23% to 90% [6]. Minimising weed seed rain should therefore be a key component of an IWM strategy [7]. However, it is important that herbicides are not the exclusive tool to achieve this, as, this will increase the risk of resistance developing. Non-chemical approaches, such as HWSC, must also be used.

There is a perception that weed seedbanks are difficult to deplete. It is true that completely eliminating the weed seedbank is impossible, but, seed banks can and are depleted by both natural and artificial processes, sometimes quite dramatically. Seed predation both by vertebrates (e.g., rodents, birds) and invertebrates (e.g., ground beetles) can be substantial e.g., losses as high as 90% have been recorded [23]. Seeds are also lost from the seedbank due to physical damage and attack from many other soil organisms particularly microorganisms, such that without input of fresh seed, the seedbank declines exponentially. Table 5 gives some examples of seed longevity of a range of grasses and broadleaf weeds.

Table 5. Weed seed longevity. From [3].

Longevity	Grasses	Broadleaves
Under 1 year	Soft brome (*Bromus hordeaceus*), rye brome (*Bromus secalinus*), barren brome (*Bromus sterilis*), volunteer cereals and oats	Volunteer sunflower and linseed
1–5 years	Perennial rye-grass (*Lolium perenne*), winter wild-oat (*Avena sterilis*)	Chickweed (*Stellaria media*), cranesbill (*Geranium molle*), Californian thistle (Cirsium arvense) and mayweed (*Tripleurospermum inodorum*)
Over 5 years	Wild oat (*Avena fatua*), loose silky bent (*Apera spica-venti*), Italian rye-grass (Lolium multiflorum).	Cornbind (*Fallopia convolvulus*), charlock (*Sinapis* spp.), field poppy (*Papaver rhoeas*), speedwells (*Veronica* spp.), volunteer oil seed rape, orache (*Atriplex patula*) and many others.

3.1.3.1. The half-life of the weed seedbank

Rather than considering the weed seedbank's persistence in terms of it's maximum longevity it is better to think of it in terms of it's 'half life', a concept which is commonly used where something is undergoing exponential decay, as the 'tail' of exponential curve can be infinitely long. The half life for the weed seedbank can be surprisingly short e.g., one to three years e.g., [20, 22] and also illustrated by Table 5. The weed seedbank is therefore nowhere near as immortal as is often believed and than reducing it is not only possible but it is the core of effective IWM [7].

3.1.4. Dormancy and germination

The primary reason the weed seedbank persists is because of dormancy. Dormancy is where seeds can’t germinate even when environmental conditions are favourable, primarily due to internal processes within the seed, but also physical attributes such as a tough seed coat. It is this ability to not germinate, even in ideal conditions, that allows the weed seedbank to persist, otherwise the whole seedbank would germinate in good conditions and could be eliminated.

When seeds are released from a plant they have three types of dormancy (Figure 6):

- Primary dormancy is where the seed is already dormant;
- Conditional dormancy is where, if the seed finds itself in a good environment for germination it will germinate, if it is in a poor environment, it will enter the dormancy cycle;
- Non-dormant, is where if the seed finds itself in any environment where it can germinate it will, else it will enter the dormancy cycle.

Unlike germination which is an irreversible, fully off or fully on, process, dormancy is both cyclical and proportional. This creates the dormancy cycle in Figure 6 where a seed cycles between fully dormant partly dormant and fully non-dormant.

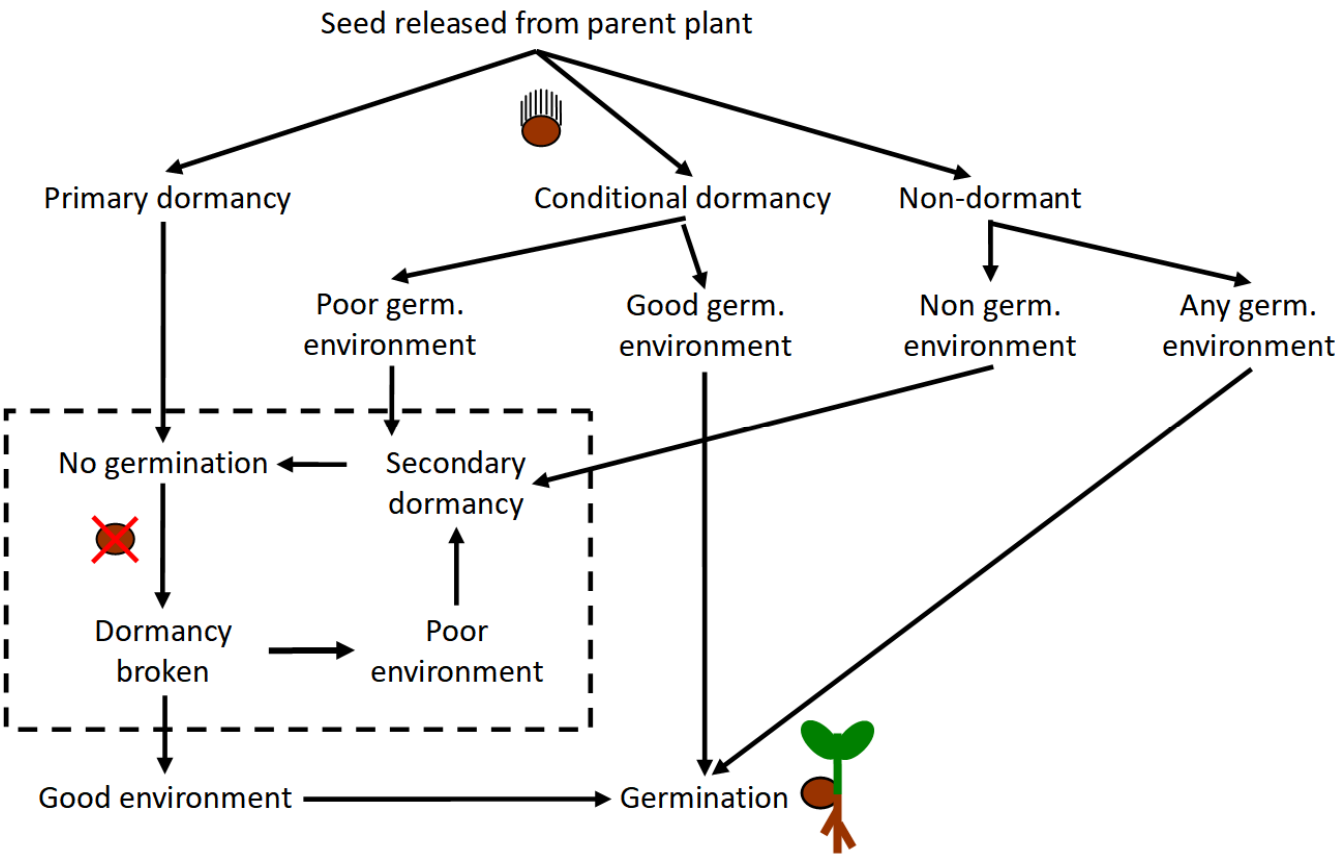


Figure 6. Diagram of the main dormancy and germination 'routes' taken by a seed. Dashed box contains the dormancy breaking and induction cycle.

The interaction of germination and dormancy underpins a number of weed management approaches. For example, management of oil seed rape (OSR) seed lost at harvest, is best managed by rolling or very lightly cultivating it into the soil surface to create good germination conditions, so the seed can be germinated and the seedlings killed. If instead the seed is ploughed under, it then finds itself in unsuitable germination conditions and will enter the dormancy cycle, and, as the seed is progressively brought back up to the surface, it will then germinate, producing flushes of OSR over the following years. In comparison, if grass seed is ploughed under, it will also enforce dormancy, but, as most grass seed is soft (section 3.1.2) most of it will die after a few years, and so be eliminated from the seedbank. All mainstream crop seeds have had primary and conditional dormancy bred out of them so they will germinate as soon as they are sown into suitable conditions.

3.1.5. Germination factors

Seeds continually monitor their environment to determine if conditions are good for germination, and therefore successful establishment, growth and ultimately seeding. The main factors seed monitor are:

- Temperature.
  - Absolute temperature - optimal range for each weed species;
  - Diurnal (day-night) variation - a signal of the presence / absence of plant cover and also proximity to the soil surface where diurnal variation is largest.
- Nitrate - higher levels are an indication of soil disturbance;
- Light - presence of light indicates proximity to soil surface, soil disturbance and/or lack of plant cover;
- Water - sufficient water is required for plant growth;
- Oxygen - increased levels indicates proximity to soil surface and/or soil disturbance and it is required for plant growth;
- Carbon dioxide - decreased levels indicates proximity to soil surface and/or soil disturbance;
- Allelopathic compounds - lack of indicates absence of existing vegetation and therefore competition.

Annual plants and weeds are species that have evolved to grow in disturbed ground e.g., rock falls, a tree uprooting in a forest, flooding from rivers. This means there is an absence of competition (e.g., compared with woodland, pasture), so their evolutionary strategy is to germinate, emerge and grow as fast as possible and set seed, before the soil is disturbed again or perennial plants establish and out-compete them. The above factors therefore indicate the environmental conditions to the seed, particularly if the soil has been disturbed. They also indicate to a seed its depth in the soil and therefore if it is likely to be able to reach the surface if it germinates (section 6.3.3).

The reasons tillage is so effective at encouraging weed seeds to germinate is it enhances all of the above factors creates by creating disturbed ground, which is what annual cropping weeds have evolved to exploit.

Light also has a critical role to play post crop establishment.

3.1.6. Light and germination

Some seed's germination is influenced by light. Seeds can be positively photoblastic in that they require a period of light exposure to germinate, or negatively photoblastic in which means they need a period of darkness to germinate. The amount of light required by positively photoblastic seeds to initiate germination can vary from a brief flash from a dim source such as tractor lights, to, prolonged exposure to full sunlight. A considerable amount of research was undertaken in the 1990s to see if the requirement for light exposure for some weed species could be used for control, but, the results were unpredictable so it has fallen from favour.

Seeds can also sense the ratio of red to far-red light which means they can determine if there is existing plant cover due to the light they receive having been filtered by plant leaves and therefore coloured green with low levels of red light as this is absorbed by chlorophyll. Inhibiting weed seed germination through light filtered by plant leaves is a vitally important means of weed management (section 6.4.1).

3.2. Germination, growth, flowering and seeding dates

The time of year when the main weeds on a property germinate, grow, flower and set seed can be important to know for a number of IWM techniques, particularly minimising weed seed rain.

3.2.1. Annual weeds

Annual weeds have a germination peak in spring, with few germinating mid summer, then a smaller peak in autumn, and few germinate in the middle of winter. Individual weed species can be generalists germinating in both spring and autumn, while others can only germinate in spring (summer annuals) or autumn (winter annuals). At the individual plant species level, the timing of germination is highly variable and driven by a range of factors, with soil temperature often being a key driver, so it can vary considerable over quite small geographical distances. It is therefore a good idea to record the dates over which your main weed species germinate, and, to link that not just to calendar date but soil temperature as well. This will allow you to be able to predict the emergence dates of your key weeds.

The time between germination and flowering / seeding is also highly variable, some species, e.g. shepherd's purse (*Capsella bursa-pastoris*) and *Poa annua,* can start flowering and setting seeds within a handful of weeks of germinating, while others require many months before they flower and seed. Flowering may also be driven by daylength (photoperiodism).

- Short-day plants flower when the night lengths exceed their critical photoperiod. They cannot flower under short nights. e.g., Fat hen (*Chenopodium album*).
- Long-day plants flower when the night length falls below their critical photoperiod. e.g., Henbane (*Hyoscyamus niger*).
- Day-neutral plants are unaffected by day/night length, rather they flower depending on factors such as development stage, age, size, and environmental stimuli such as cool temperatures.

Short and long-day plants are also subdivided into:

- Obligate photoperiodic plants can only flower if the day/night lengths meet their requirements;
- Facultative photoperiodic plants are more likely to flower if the day/night lengths meet their requirements, but they can flower at other times due to other factors, e.g., plant size.

As for germination, it can be valuable to record when your most problematic weeds start to flower and set seed so you gain an understanding if they are photoperiodic or not and if they are photoperiodic their flowering and therefore seeding dates.

3.2.2. Biennial

Biennials nearly always germinate in spring to allow them the summer to build up their reserves for overwintering, and then flower in the following summer, before dying.

3.2.3. Perennials

Perennials mostly flower and set seed in the from the middle of summer into autumn. A key division is whether they become fully dormant in winter and loose all their above ground foliage, e.g. Californian thistle (*Cirsium arvense*), or if they retain their foliage year-round, e.g., docks (*Rumex* spp.).

3.3. Competition

The primary reason weeds are managed in cropping systems is because they compete with the crop and therefore reduce yield and economic return - hence why they are defined as weeds (section 1.2). There is significant variation in the competitive ability of different weeds. Table 6 ranks the competitive ability of a range of weeds in wheat crops, in the UK as an example.

Table 6. Competitive ability of common weeds in wheat. From [3].

Competitive ability Number of plants/m^2 that would typically result in a 5% yield loss in wheat	**Weed species**
Very competitive 0-5	Barren brome (*Bromus sterilis*) cleavers (*Galium aparine*), Italian rye grass (Lolium multiflorum), wild-oat (*Avena fatua*).
Competitive 12-17	Cornbind (*Fallopia convolvulus*), charlock (*Sinapis* spp.), field poppy (*Papaver rhoeas*), Californian thistle (*Cirsium arvense*), scentless chamomile / mayweed (*Tripleurospermum inodorum*).
Moderately competitive up to 25	Chickweed (*Stellaria media*), fat hen (*Chenopodium album*), forget-me-not (*Myosotis arvensis*), willow weed (*Persicaria maculosa*).
Less competitive 50 and above	Fumitory (*Fumaria officinalis*), Scarlet pimpernel (*Anagallis arvensis*), Sheppard's purse (*Capsella bursa-pastoris*), dove's foot cranesbill (*Geranium molle*)red dead nettle (*Lamium purpureum*), annual meadow grass (*Poa annua*), wireweed (*Polygonum aviculare*), groundsel (*Senecio vulgaris*), scrambling speedwell (*Veronica persica*), field pansy (*Viola arvensis*).

However in arable crops the crop also 'fights back' in that they compete strongly against the weeds, especially the larger and denser crops like cereals. Competition also occurs both above and below ground, with root competition often the more important, i.e., more than 50% of plant competition is underground. This again is why cereals are strong competitors because of their fibrous root systems that penetrate more of the soil. Increasing the competitive ability of the crop is an important weed control technique in arable crops.

3.3.1. Allelopathy

Allelopathy is a biological effect where an organism produces one or more allelochemicals that affect the germination, growth, survival, and reproduction of other organisms. The effect can be both positive (boosts growth of other plants) and negative (inhibits or kills other plants), though in agriculture it almost exclusively means a negative interaction. There is often considerable interest from farmers about the potential of using allelopathy for weed control and if a highly effective biological / ecological weed management outcome is due to allelopathy. However, while there is considerable potential, allelopathy has a poor reputation in weed science as while many lab and glasshouse experiments show positive results they exceptionally rarely translate into the field. It also requires carefully designed experiments to separate the effects of competition and true allelopathy between crop and weeds, and, at a practical field level, it is mostly immaterial if the interaction between crop and weeds is due to competition or allelopathy or both. Therefore while it is a genuine and interesting scientific phenomenon, in terms of practical weed management it is mostly considered irrelevant. One exception is where crop cultivars are bred to be strongly allelopathic, but, it is difficult to breed for as measuring it is complex, and, it must compete with a growing list of attributes, e.g., pest and disease resistance, that breeders are also called upon to address.

3.4. Physical attributes of weeds for mechanical control

To kill a weed with herbicides a biochemist needs to understand a plants biochemistry and how it interacts with the herbicide's chemistry. To kill a weed mechanically, farmers have to understand how the physical attributes of a weed interacts with the weeding tools at their disposal.

3.4.1. Plant morphology

Morphology is the physical form and external structure of plants. For example, a prostrate or erect, large or small, tough or sappy, creeping roots, creeping stems (stolons and rhizomes) etc. Much plant morphology is pretty obvious just by looking at a plant, digging them up and from general farming experience. However, the key is to think about how a particular weeding tool is going to interact with a given weed's morphology and therefore how effective it will be.

3.4.2. Plants can only grow from their meristems

Plants can only grow from their 'meristems' i.e., buds. Growth in biology is defined as cell division, not, just enlargement. The meristem is the only site in plants containing undifferentiated / meristematic cells, and is therefore the only place where cell division occurs. Once the cells have differentiated, e.g., into a root, stem, leaf, etc., they cannot undergo further cell division. There are three main types of meristems:

- Shoot buds - produce new leaves, stems and flowers and exist in the leaf axis and tip of the plant;
- Root tips - roots have a meristem at their tip;
- Cambium - produces new vascular tissues (phloem and xylem) and the bark which allows plants to increase the width of their stems / trunks.

That plants can only grow from their meristems is critical for many physical weed control approaches. See en.wikipedia.org/wiki/Meristem for more detailed information on meristems.

3.4.3. The hypocotyl or mesocotyle / coleoptile zone

A key concept in the physical attribute of weeds / plants is the hypocotyl in broadleafs (dicotyledons) and the coleoptile and mesocotyle in grasses (monocotyledons). This is the zone between the cotyledon leaf or leaves and the start of the root system (Figure 7).

Figure 7. Diagram of broadleaf / dicotyledon and grass / monocotyledon showing seedling structure (left) mature cleavers (*Galium aparine*) plant showing hypocotyl between the true roots and true shoots.

Severing annual plants through the hypocotyl or mesocotyle / coleoptile is fatal, as this disconnects the light and carbon dioxide gathering system of the true stem from the water and nutrient gathering system of the true roots. If the same plant was severed just above the first true leaves then it can regrow from the buds in the true leaf axils, or, if the plant was severed just below the start of the true root system, then the roots can regrow. Therefore, for mechanical control of annual weeds the hypocotyl and mesocotyle / coleoptile zone is a key target. Targeting the hypocotyl or mesocotyle / coleoptile zone is akin to ring barking / girdling a tree, as while it not severing the tree at the hypocotyl, it disconnects the true shoots and true roots which will cause the tree to (eventually) die (of starvation).

3.4.4. Dedifferentiation

In general, the different meristem types, (shoot, root, cambium) only produce their specified tissues, i.e., shoot meristems only produce shoots and leaves, roots only roots. However some plants, particularly perennials, can de-differentiate their meristems, e.g., true shoot meristems can produce true roots, the cambium can produce true shoots and sometimes true roots, and root meristems can produce true shoots (Figure 8).

Figure 8. Examples of the four forms of dedifferentiation.

Dedifferentiation is the process underpinning vegetative propagation of plants, e.g., a two node shoot cutting, where the bottom node is placed in appropriate media will produce roots, and therefore create a new plant. Plants that can dedifferentiate can be particularly hard to kill as they can regrow a whole plant from only a small portion of tissue, so severing them at the hypocotyl will set the plant back but not kill it. A range of different approaches are required to physically kill weeds that can dedifferentiate and they are often specific to the type of dedifferentiation and even specific to an individual weed species.

4. Herbicide management to combat resistance

How herbicides are used is the key driver of plants evolving resistance. Ironically, the best way to avoid resistance is to stop using herbicides, the less they are used the longer they will remain effective. This clearly points to the key message of this booklet - Integrated Weed Management: using **all** the tools in **all** the toolboxes. The greater the diversity of tools that are used for weed control, the less anyone tool gets used, and therefore the lower the chance of resistance developing to that tool. Also only applying herbicides when there is an economic return means that herbicides are less likely to be used unnecessarily and will save money.

However, for most farmers, completely stopping herbicide use is neither practical or desirable - as it reduces the total number of tools being used. Therefore when using herbicides there are a number of actions that can taken to minimise resistance developing. This section outlines those actions and the underpinning science.

4.1. How herbicide resistance occurs

Herbicides do not cause plants to develop HR, i.e., create genetic mutations. Rather, in any population of plants there already exist individuals with random genetic variation that makes them resistant. Indeed plants had resistance genes in them well before the first herbicide was invented. For example, a herbarium specimen of Black grass (*Alopecurus myosuroides*) collected in 1888, was found to have ACCase resistant genes, 90 years before ACCase-inhibiting herbicides were first used [18]! Instead, using herbicides 'selects' (as in Darwin's 'natural selection') the plants, that by genetic chance, happen to already have resistance. This is more akin to 'artificial selection', i.e., breeding, in that herbicides kill 'unfit' plants leaving only the 'fit' ones, same as a stockman culls unfit livestock and keeps the fit ones.

Estimates of the standard spontaneous mutation rate that creates a herbicide resistant plant is hard to estimate but is considered to be between 10^{-8} and 10^{-9} [8, 18] which is very small, but, considering the seedbank of a single weed species can be 10^{7} seeds/ha, and there are many weed species per ha, and many hectares on an individual farm, then the vastly larger number of weed seeds and species hugely outnumbers the very small mutation rate. This means that there could be hundreds of individual weeds on a farm that have spontaneous mutations that make them HR [18].

4.1.1. Susceptible to resistant population shift

The shift from one weed plant having a mutation that makes it HR to a paddock being covered in HR weeds is a numbers game. With each spraying event, susceptible weeds die, resistant weeds survive, so the proportion of resistant to susceptible weeds tips in favour of the resistant weeds, therefore, they have more progeny so resistant weeds make up a larger and larger proportion of the population as each spraying event occurs (Figure 9).

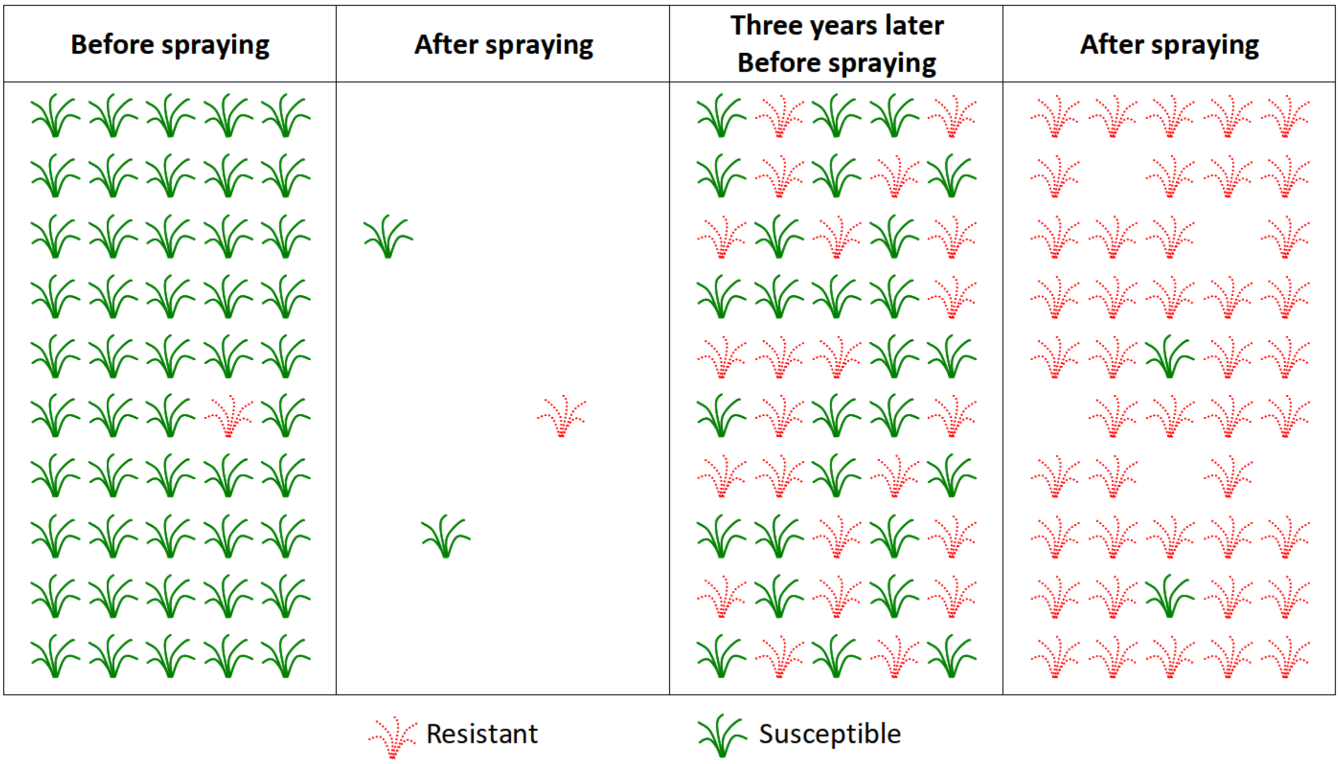


Figure 9. The change in the proportion of HR weeds. After [24].

The proportion of resistant weeds is initially very low, but, if the same MoA is repeatedly applied to the same paddock, then, the proportion of resistant weeds will start to increase exponentially, giving the impression that the resistant weeds have suddenly appeared, while they have actually be present at low populations for several years before hand (Figure 10).

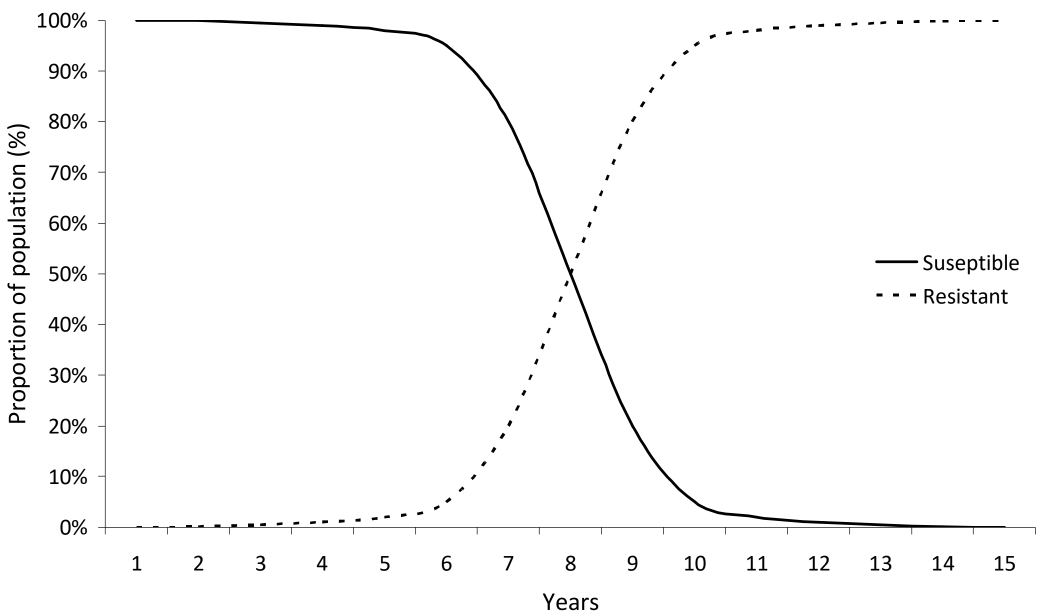


Figure 10. A generalised graph of the impact of repeated herbicide application of the same MoA on the proportion of susceptible and resistant weeds. After [24].

As the development of resistance is a numbers game, then the numbers of weeds exposed to herbicides should be minimised, as the smaller the number of weeds exposed the smaller the chance that a HR weed will be sprayed and survive, i.e., spraying a paddock with small population of weeds is unlikely to result in resistant weeds being sprayed, but, if the population is very high, e.g., a carpet of weeds, the chances of spraying a HR weed is almost guaranteed. Therefore, weed populations should be minimised by non-chemical means as much as possible before herbicides are used.

4.2. Where do herbicide resistant weeds come from?

The short answer to the question: where do the resistant weeds on my farm come from? is your farm. The longer answer, is that while there are a number of routes for HR plants to come onto a farm, either as seeds, on machinery, in purchased products, e.g., straw, etc., or as pollen, these routes, while not unimportant (section 4.3.4) are considered less likely to be the source of resistant weeds, that weeds that evolve resistance on-farm.

There is also a strong interaction with on-farm practices that combat HR and the presence of HR weeds, in that if a farm has a comprehensive and effective Herbicide Resistance Management Strategy (HRMS) with the aim of preventing HR weeds evolving on farm, then, even if HR weeds come onto the property from outside, they, are likely to be kept at low levels. If a farm is not practicing good HR management, then, when HR weeds do enter the property, then their population will likely quickly expand (as per Figures 9 & 10) and there will also be a greater number of HR weeds that evolve on-farm, which will also be able to build larger populations .

So, regardless of the source of HR plants, on or off farm, whether those weeds flourish or are suppressed depends on the farm's weed management strategy. In short a farms HR weeds are mostly its own responsibility, not the farm down the road.

4.3. Resistance mechanisms

Most herbicides work by their active chemical binding to specific molecules in plants (often proteins and enzymes), and disrupting the function of the molecule, which, if the molecule's function is critical for the plants survival (e.g., producing a particular amino acid), then the plant dies. The way a herbicide chemical binds to the molecule in a plant is like a key in a lock - a precise fit. If the lock (the plant molecule) changes shape, even a tiny bit, the key (the herbicide chemical) may no longer fit, and, if it can't fit (bind), it can no longer stop the molecule functioning, so the plant survives.

However, plants, are a massive collection of molecules, and it can take some time for the herbicide chemicals that are applied to the plants foliage or taken up by the roots, to reach the specific molecule they bind to, and, depending on the function of the plant molecule and its position in a plants biochemical pathways, it can take some time, for the plants to die.

This results in there being two main ways that herbicides resistance develops: 'target site resistance'; and 'non-target site resistance'.

4.3.1. Target site resistance

The classic form of target site resistance is where the target molecule is changed such that the herbicide chemical no longer binds to it - the lock and key analogy. This can confer complete immunity to the herbicide - i.e., increasing the dose has no effect. It used to be believed this was how all target site resistance worked (the classic form), but, it is now realised the picture is more complex as the target site mutations can vary in their strength, strong to weak, e.g., the key no longer fits at all, through to, the key fits but, it needs a bit more force (a higher dose) to turn.

The second type of target site resistance is where many more copies of the plant molecule the herbicide binds to, thereby 'soaking up' the herbicide. This is called 'gene amplification', and is less common than single target site mutation.

4.3.2. Non-target site resistance

Non-target site resistance is where the herbicide chemical is stopped or impeded from reaching the target site, for example, the plant metabolises the herbicide chemical into a non-harmful form, or, it moves it to where it can't kill the plant, e.g., leaf tips, or, stores it in vacuoles inside cells, etc.

Non-target site resistance was initially thought to be of lesser importance, but, it is now being shown to responsible for considerably more cases of resistance than first thought and is actually of major importance, potentially due to the many different mechanisms by which herbicides can be prevented from reaching their targets. It was also initially thought that this form of resistance would be partial, and, that increased herbicide dose would then still kill the weeds, it is now realised that this is also not the case, and that near total resistance to any dose can occur.

4.3.3. Cross-resistance and multiple resistance

Cutting across the above two types of resistance are cross and multiple resistance.

Cross-resistance is where resistance to one herbicide makes the weed resistant to another herbicide. This is mostly resistance to herbicides within a MoA but can also be between MoAs. It applies both to target and non-target resistance.

Multiple resistance, is akin to stacking in genetically engineered crops: a weed evolves two or more different resistance mechanisms to two or more different herbicides, i.e., the mechanisms are independent of each other. The mechanisms can be either, or, both, target and non-target.

4.3.4. Herbicide resistant gene flow / movement

There are two means by which HR genes move among paddocks and among farms: as seeds and pollen.

There is a substantial amount of research, going back to the dawn of weed science, as well as practical farm experience, of how seeds are moved around both within and between farms, and all the way up to global weed seed movement. Equipment is a key means of weed seed movement, including tractors and cultivators where the seed is in soil attached to the machines, and especially in harvest equipment, not only the header / combine, but, in transport trucks and other equipment e.g., bailers. Planting seed is also another source, with the recent velvetleaf (*Abutilon theophrasti*) introduction via fodder beet seeds an example of this route. Brought in feed is an important route, especially hay and straw, but also grains, and to a lesser extent ensiled feed as fewer plants have produced viable seeds at the time of harvest and ensiling also kills weed seeds, particularly grasses, and to a lesser or negligible extent broadleafs. HR gene movement via seeds can therefore be both over short (e.g., within and between paddocks) and long distance, between farms, regions and countries.

Movement by pollen is much more restricted. The distances pollen can travel ranges from a few hundred meters to a few kilometres depending on species. Pollen can travel very long distances on a strong wind, but, the further it travels the more 'diluted' it becomes due to the increasing volume of atmosphere that it is traversing, such, that the likelihood of it finding a receptive flower becomes very unlikely after a few kilometres. For insect vectored pollen the distance is similar as most insects only move hundreds of meters, with a few kilometres being the maximum, including for honey bees.

Pollen of a particular weed species is also only present at specific and often short, e.g., a few weeks, to a few months, periods during the year, i.e., when the weeds are flowering.

The short duration and limited dispersal distances of pollen, compared with the year round presence of seeds, their ability to remain viable for years, and that the can be dispersed long distances on equipment, feed, planting seed etc., means pollen is a negligible route for dispersal of HR genes and seed movement is the dominant form. Also pollen movement cannot be controlled while seed movement can be managed. Therefore active management to reduce the movement of weed seeds among farms is therefore an important management tool and is discussed in section 6.8.

4.4. Herbicide resistance risk factors

The risk that a particular weed species develops resistance to a given herbicide depends on a range of risk factors. The three overarching HR risk factors are:

- Herbicide MoA;
- Weed species;
- Farm management practices.

Each of these has multiple sub components (Figure 11).

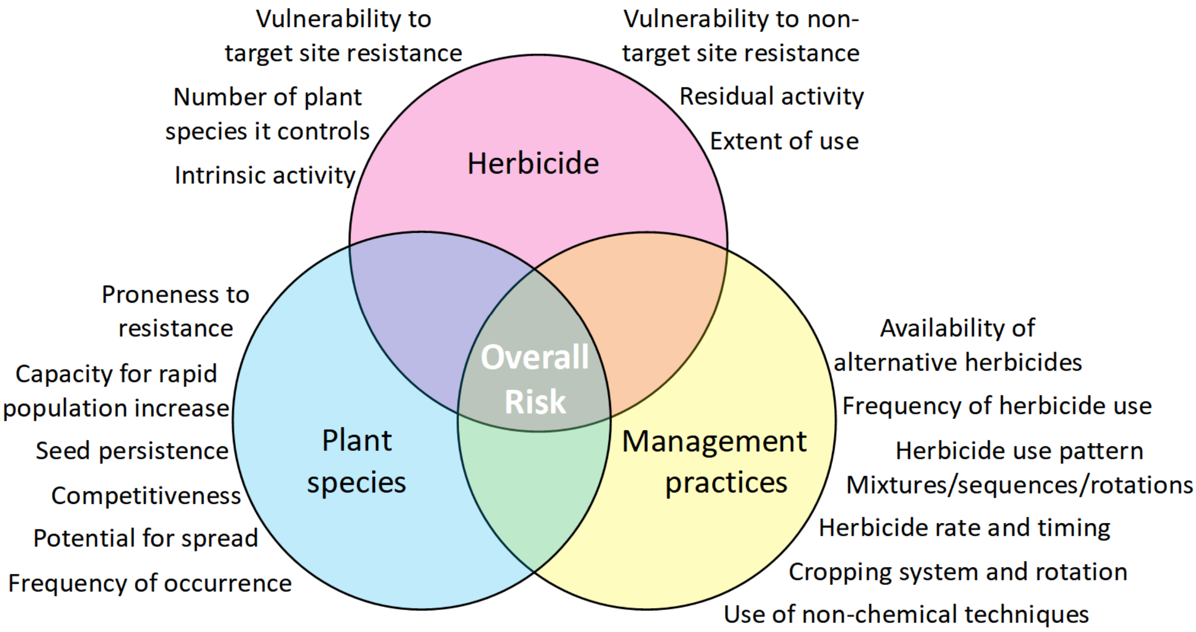


Figure 11. Components of the three main herbicide resistance risk factors. From [18].

This shows that there are multiple factors that can be manipulated to reduce the risk of a plant developing resistance. Management practices by definition are under the land managers control. These include non-herbicide issues such as the design of cropping systems, non-chemical techniques, as well as herbicide management. Management practices and herbicide properties overlap, as farmers can choose which herbicide to use, and different herbicides have different risks of resistance. Farmers are also in control of how a particular herbicide is used, e.g., mixtures, rates, application, timing etc. While farmers do not control the properties of individual plant species, they are active managers of the weeds on their properties for the standard objective of reducing weed competition to increase yields. With the knowledge that some weed species are more at risk of evolving resistance, or that larger weed populations increase the risk of resistance developing, management decisions can be made to reduce these risk factors as well. This shows that farmers have a considerable ability to manage and limit HR weeds on their farms.

4.5. Herbicide risk factors for resistance

Following Figure 11, the first of the three overarching risk factors for HR are the herbicide's MoA.

4.5.1. New Zealand herbicide mode of action (MoA) classification and group codes

Table 7 shows the group codes, mode of action (MoA), chemical family, active ingredient and product names for herbicides available in New Zealand. All MoA in this handbook, and, New Zealand herbicide literature use these MoA group codes and classification system.

Table 7. Mode of action (MoA) groupings used in New Zealand as of November 2019 from resistance.nzpps.org/index.php?p=herbicides/mode_of_action. * for an AI means not registered or no longer registered in New Zealand.

Group Code	Mode of Action	Chemical Family	Active Ingredient	Product examples
A	Inhibition of acetyl CoA carboxylase (ACCase)	Aryloxyphenoxypropionates "fops"	clodinafop-propargyl	Mandate, Ultima
			fenoxaprop-P-ethyl	Coronet, Foxtrot, Panther, Puma
			fluazifop-P-butyl	Fusilade Forte
			haloxyfop-P	Crest, Gallant Ultra, Hurricane, Ignite, Scorp Ec, Valiant
			quizalofop-P-ethyl	Leopard
		Cyclohexanediones "dims"	clethodim	Arrow, Centurion, Cleo, Sequence, Vega
			sethoxydim*	Stopa
			tepraloxydim	Aramo
			tralkoxydim*	No product
		Phenylpyrazoline "dens"	pinoxaden	Twinax
B	Inhibition of acetolactate synthase ALS (acetohydroxyacid synthase AHAS)	Sulfonylureas	chlorimuron-ethyl	Classic
			chlorsulfuron	Adama Chlorsulfuron
			flazasulfuron	Katana
			foramsulfuron*	No product
			halosulfuron-methyl	Sempra
			iodosulfuron	Hussar
			mesosulfuron-methyl	Component of Othello
			metsulfuron-methyl	Escort, Answer, Associate, Mustang, Prism, Reply, Synergy Met600, Ultimate, Zeal
			nicosulfuron	Adapt, Guardian Plus
			primisulfuron-methyl	No product
			thifensulfuron-methyl	Backup, Chord, Harmony, Ranger, Synergy Thifen
			tribenuron-methyl	Donaghys Sprayoff Mate, Granstar, Sero Wg
		Imidazolinones	imazapyr	Unimaz 250 Sl
			imazethapyr	Equate, Spinnaker
		Triazolopyrimidines	florasulam	No product
			flumetsulam	Aim, Blast, Preside
			pyroxsulam	Simplicity

Group Code	Mode of Action	Chemical Family	Active Ingredient	Product examples
C1	Inhibition of photosynthesis at photosystem II	Triazines	ametryn*	No product
			atrazine	Atrazine, Atraflo
			cyanazine	Bladex 50Sc, Bruno
			desmetryn*	No product
			prometryn	Gesagard 500Fw, Prometryn, Prominent
			propazine	Agpro Propazine 500
			simazine	Agpro Simazine 500, Gesatop 500Fw, Simaflo
			terbumeton*	No product
			terbuthylazine	Gardoprim, Assett, Batallion, Tag G2, Terbaflo, Terminator Gta, Timberwolf 900 Wg, Topogard, Tyllanex, Velgard
			terbutryn	Batallion Sc, Terbo Flo, Topogard
		Triazinones	hexazinone	Agpro Hexagran, Agpro Hexol, Velpar, Viper
			metamitron	Agpro Metamitron, Goltix Flo, Mitron 70Wg
			metribuzin	Jazz, Metriphar 48Sc, Sencor 600 Sc
		Uracils	bromacil	Chemagro Terminex-A, Uragan Wg
			terbacil	Sinbar
		Pyridazinones	chloridazon	Chloronion, Flag
		Phenyl-carbamates	desmedipham	Component of Betanal Quattro, Rifle
			phenmedipham	Component of Betanal Quattro, Rifle
C2	Inhibition of photosynthesis at photosystem II	Ureas	diuron	Agpro Diuron 800, Chemagro Terminex-A, Karmex, Krovar I Df
			isoproturon	Cougar, Protugan, Twister
			linuron	Afalon, Linex Flo, Linuron
			methabenzthiazuron	Tribunil
C3	Inhibition of photosynthesis at photosystem II	Nitriles	bromofenoxim*	No product
			bromoxynil	Bromotril, Emblem Flo, Image, Jaguar
			ioxynil	Elliotril, Iotril
		Benzothiadiazinone	bentazone	Broadstar, Delete, Dictate 480, Pulsar, Quasar
		Phenyl-pyridazines	pyridate*	No product
D	Photosystem-I-electron diversion	Bipyridyliums	diquat	Diquat 200, Reglone
			paraquat	Gramoxone 250, Flash, Parable, Preeglone, Pirate
E	Inhibition of protoporphyrinogen oxidase (PPO)	Diphenylethers	oxyfluorfen	Agpro Oxyfluorfen 250Sc, Brownout, Burnout
		Oxadiazoles	oxadiazon	4See, Oracle
		Pyrimidinedione	saflufenacil	Sharpen
		Thiadiazole	fluthiacet-methyl	Cadet
		Triazolinones	carfentrazone-ethyl	Affinity, Hammer, Shark, Hammer Force, Torus
			sulfentrazone	Authority Sc

Group Code	Mode of Action	Chemical Family	Active Ingredient	Product examples
F1	Bleaching: Inhibition of carotenoid biosynthesis at the phytoene desaturase step (PDS)	Pyridazinones	norflurazon*	No product
		Pyridinecarboxamides	diflufenican	Quantum, Tiger, Agpro Fairway
		Others	fluridone*	No product
F2	Bleaching: Inhibition of 4-hydroxyphenylpyruvate-dioxygenase (4-HPPD)	Triketones	mesotrione	Agpro Mesotrione 480Sc, Callisto, Primiera, Dominator, Mesoflex, Tenacity
			topramezone	Arietta
F3	Bleaching: Inhibition of carotenoid biosynthesis (unknown target)	Triazoles	amitrole	Activated Amitrole
		Isoxazolidinones	clomazone	Magister, Director
G	Inhibition of EPSP synthase	Glycines	glyphosate	Round Up, Deal, Lion
H	Inhibition of glutamine synthetase	Phosphinic acids	glufosinate-ammonium	Agpro Glufosinate 200, Commando, Scythe
I	Inhibition of DHP (dihydropteroate) synthase	Carbamates	asulam	Asulox, Dockstar
K1	Microtubule assembly inhibition	Dinitroanilines	oryzalin	Cameo, Surflan Flo, Sharpshooter
			pendimethalin	Agpro Vienna, Ruck, Stomp Xtra, Strada 400Sc
			prodiamine	Barricade
			trifluralin	Omega, Triflow, Trifluralin
		Benzamides	propyzamide	Fiera, Kerb, Polka
		Benzenedicarboxylic acids	chlorthal-dimethyl	Chlor-Back, Dacthal
K2	Inhibition of mitosis / microtubule organisation	Carbamates	chlorpropham	Alliacine, Chlorpropham, Fruitfed Chloro-Ipc
			propham*	No product
			carbetamide*	No product
K3	Inhibition of cell division	Chloroacetamides	acetochlor	Acetochlor, Maize Guard, Roustabout, Sylon 840, Acierto, Joker 840
			alachlor	Alanex, Corral, Merit, Taipan
			dimethenamid-P	Frontier-P
			s-metolachlor	Dual Gold, Meteor
			propachlor	Ramrod
		Isoxazoline	pyroxasulfone	Sakura
		Oxyacetamides	flufenacet	Component of Firebird
L	Inhibition of cell wall (cellulose) synthesis	Alkylazines	indaziflam	No product
		Nitriles	dichlobenil	Prefix-D

Group Code	Mode of Action	Chemical Family	Active Ingredient	Product examples
N	Inhibition of lipid synthesis - not ACCase inhibition	Thiocarbamates	prosulfocarb	Boxer 400
			triallate	Avadex Xtra
		Benzofuranes	ethofumesate	Expo 500, Nortron, Pasture Clear, Beetall Pd
		Chloro-carbonic-acids	TCA	No product
			flupropanate	Taskforce
			2,2-dichloropropionic acid	Chemagro Dalapon, Teedal
O1	Action like indole acetic acid (synthetic auxins)	Phenoxy-carboxylic-acids	2,4-D	Baton, Pasture Kleen
			2,4-DB	2,4-DB
			dichlorprop-P	Corasil
			MCPA	Agritone 750, Clean Sweep, Maestro
			MCPB	Nufarm MCPB 400, Soft Touch
			mecoprop	No product
			mecoprop-P	Duplosan
O2		Benzoic acids	dicamba	Agcare Dicamba 500, Bandit, Cutlass
O3		Pyridine carboxylic acids	aminopyralid	T-Max, Tordon, Vigilant Ii
			clopyralid	Archer, Cobber, Monarch, Multiple, Versatill
			fluroxypyr	Saxon, Solstar, Starane, Tomahawk
			picloram	Tordon, Vigilant
			triclopyr	Agpro Triclop 600, Grazon
O4		Arylpicolinate	halauxifen-methyl	Component of Paradigm
Z	Unknown	Arylaminopropionic acids	flamprop-M-isopropyl	Crusader
		Organoarsenicals	MSMA*	No product
		Other	benzalkonium chloride	Graphic
			chloropicrin	Pic Plus
			dazomet	No product
			endothal	Aquathol K
			fatty acids	Agpro Bio-Safe
			metam sodium	No product
			methyl bromide	No product
			palm oil derived fatty acids	No product
			pine oil	Organic Weedfree Rapid
			gibberellic acid	Donaghys Gibbstartmax

The herbicide MoA classification in Table 7 as used in New Zealand is the same as the Herbicide Resistance Action Committee (HRAC) MoA www.hracglobal.com. There are two other herbicide classification systems used globally, the WSSA (Weed Science Society of America) and the Australian system. More detailed information on the three systems and also more detailed information on the modes of action (also called sites of action SoA) can be found at www.weedscience.org/Summary/SOADescription.aspx.

The Grains Research and Development Corporation (GRDC) in Australia have a detailed technical document on herbicide mode of actions available from grdc.com.au/__data/assets/pdf_file/0027/293490/GRDC-GrowNotes-Herbicides.pdf This also includes information for each MoA on the effects of environmental conditions on activity and spray application as well as spray application details including adjuvants and water quality. Note the Australian MoA codes differ slightly from NZ - see directly above - so always check the MoA and AI by name when using Australian herbicide information sources.

While there are different coding systems for herbicide MoAs globally, the herbicide MoA chemistry are exactly the same everywhere around the world, i.e., there are no MoAs specific to any particular country. Formulations, brand names etc., do vary, but the underlying chemistry is exactly the same. Therefore the lessons on herbicide resistance from overseas are directly applicable to New Zealand.

4.5.2. Relative herbicide resistance risks for different modes of action (MoA)

As Figure 11 shows, herbicide MoA is an important variable in HR risk, and there is significant variation in the number of plant species resistant to different herbicide classes, as illustrated by Figure 3 (page 11). Figure 12 shows the number of plant species that are resistant to different herbicide modes of action, and categorises them into high, medium and low risk of plants species developing HR to them.

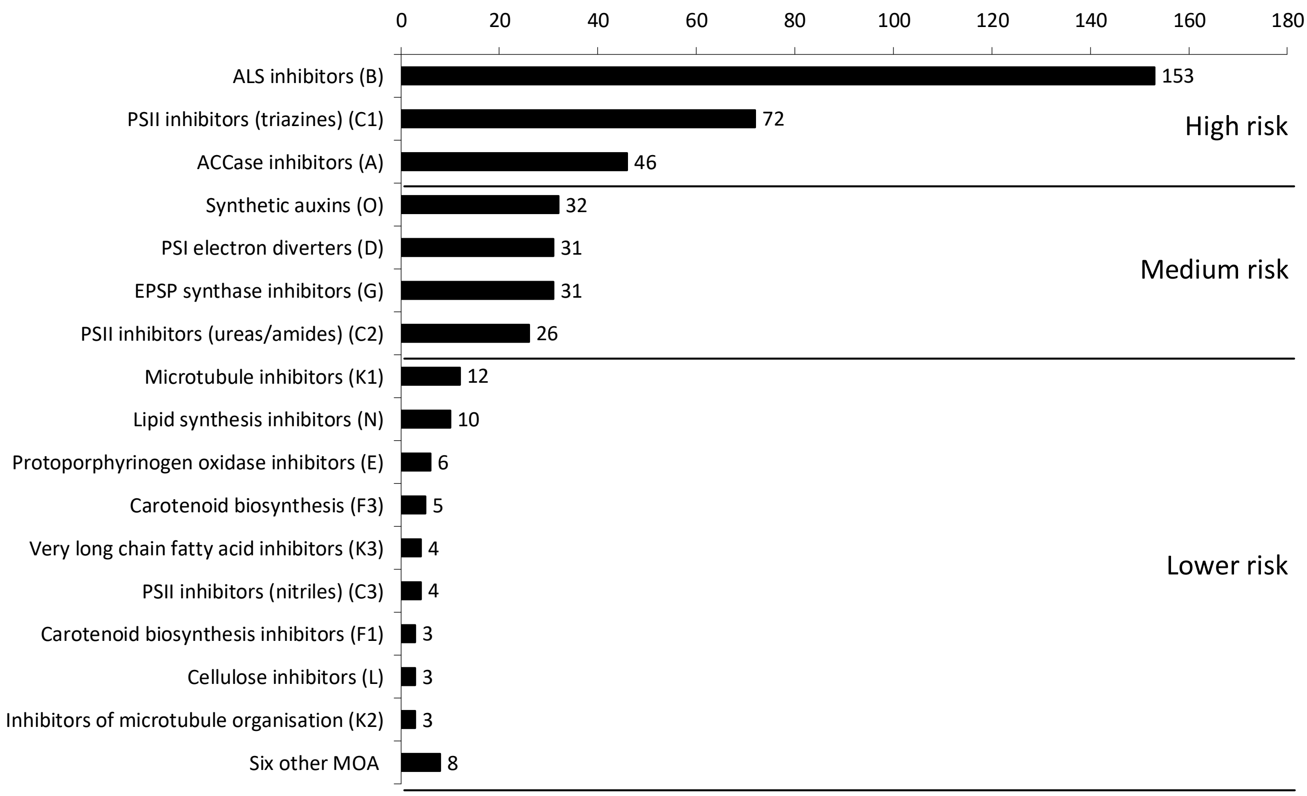


Figure 12. The number of plant species resistant to different mode of action (code) classes globally, and the categorisation into high, medium and low risk of herbicide resistance [18].

Figure 12 shows there is a dramatic difference in the number of plant species resistant to different herbicide MoAs. Where ever possible, and especially if other risk factors such as plant species are high (Figure 11), herbicides with a lower resistance risk should be used in preference to herbicides with a higher risk.

The number of MoAs a weed species is resistant to and the number of weed species resistant to a particular MoA are not entirely due to the genetics of the weeds nor the chemistry of the herbicide, i.e., internal factors but also external factors such as how common the weed species are and the size of their in-field populations and the range of crops a MoA can be used in i.e., is it a widely used herbicide or restricted to niche applications. Figures 11 & 12 are therefore a general guide as to the likelihood of resistance based on real-world data, rather than a bottom up numerical risk assessment.

4.6. Plant species risk factors for resistance

Plant species is the second overarching herbicide risk factor in Figure 11.

Figure 4 in section 2.1 shows the plant species with the most resistance to multiple MoA. Figure 13 shows the same data but grouped by plant family.

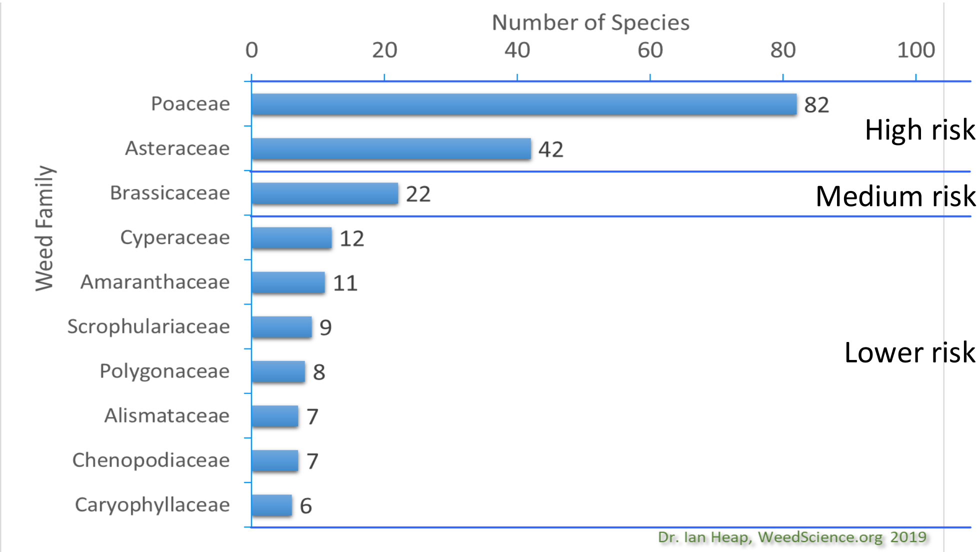


Figure 13. Number of herbicide resistant plant species by plant family, globally. From weedscience.org.

The grasses (Poaceae) the sunflowers (Asteraceae) are at the highest risk of developing resistance and brassicas (Brassicaceae) at medium risk. The risk information in Figures 12 & 13 need to be used together to identify the highest risk herbicide MoA × plant family combinations, which is provided below.

4.6.1. Global genera × MoA resistance table

Table 8 shows the main agricultural weedy genera present in New Zealand, and the number of species in each genus that are resistant to the main herbicide MoA's, both globally and in New Zealand. Table.9 presents a subset of the same data but sorted by the genera with the highest number of HR species and also sorted by the herbicide MoA's that have the most species resistant to them, i.e., it highlights the highest risk plants and MoAs at once. These tables therefore provides an indication of the likelihood of any given New Zealand weed species developing resistance to a specific MoA, as this resistance has already developed somewhere in the world. A full list of every individual plant species × MoA table is available from www.weedscience.org/Summary/SpeciesbySOATable.aspx.

When planning a herbicide program for a given crop / paddock, this table and the full species × MoA table at WeedScience.org should be consulted to see which MoA's the weed genera or species present in a given paddock have developed resistance to both in New Zealand and overseas, and, therefore, to try to choose MoA to which that weed species has not developed resistance too, or, at least only a small number of species in that genera have.

Table 8. The main global, agricultural, weedy genera, present in New Zealand, and the number of species in each genus, resistant to the main MoA groups, globally. Genus names are hyperlinked to Wikipedia. Derived from weedscience.org.

Genus	Common name	Mode of action code									
		A	B	C1	C2	D	G	K1	O	F2	Other
Agrostis	Bentgrass										1
Alopecurus	Foxtail grass	3	3	1	2	1		2			2
Amaranthus	Amaranths		9	10	2	1	4	1	3	2	8
Ambrosia	Ragweeds		2	1	1		2				1
Anthemis	Chamomiles / mayweeds		2								0
Apera	Silkybent grasses	1	1		1						0
Arabidopsis	Rockcress			1							0
Arctotheca	Cape weeds					1			1		0
Avena	Oats (wild oats)	3	3					1			7
Brassica	Brassicas		2	1			1		1		0
Bromus	Brome grasses	4	6	1	1		3				0
Capsella	Sheppard's purse		1	1							0
Carduus	Plumeless thistles						1		3		0
Centaurea	Knapweeds / cornflower		1						3		0
Chenopodium	Fat hen / goosefoots		1	4	1				1		0
Chloris	Windmill grasses			1	1		4				0
Cirsium	Plume thistles								1		0
Convolvulus	Bindweeds					1					0
Conyza	Fleabanes		3	2	2	3	3		1		1
Crepis	Hawksbeards		1								0
Cuscuta	Dodders		1								0
Cynodon	Bermuda grass						1				0
Cynosurus	Dogstail grass	1	1								0
Cyperus	Sedges		6		1						0
Datura	Jimsonweeds / thornapples			1							0
Daucus	Wild carrot								1		0
Digitaria	Summer grasses / crabgrass	4	1	1			1		1		0
Echinochloa	Barnyard grass	5	5	2	3		1	1	4		7
Ehrharta	Veldtgrass	1									0
Eleusine	Goosegrasses / crowfoot grasses	1	1	1		1	1	1			2
Epilobium	Willow weeds			2		1					0
Erigeron	Mexican daisy					1					0
Euphorbia	Spurges		1		1						1
Fumaria	Fumitory							1			0
Galeopsis	Hemp-nettle		1						1		0
Galinsoga	Gallant soldier		1	1							0
Galium	Cleavers		3						2		0
Gamochaeta	Cudweeds					1					0
Hordeum	Barley grass	2	1			2	1				0
Lactuca	Wild lettuce		1				2		1		0

Genus	Common name	Mode of action code									
		A	B	C1	C2	D	G	K1	O	F2	Other
Lamium	Dead-nettle		1								0
Lepidium	Twin cress / peppercresses					1					0
Lolium	Ryegrasses	4	3	1	2	2	3	1			11
Matricaria	Mayweeds / chamomiles		1	1							0
Nassella	Nassella tussock / needlegrass										2
Panicum	Broom corn millet / panicgrasses			2							0
Papaver	Poppies		1						1		0
Paspalum	Knotgrass						1				0
Phalaris	Phalaris / canary grasses	3	3	1	1						0
Picris	Oxtongues		1								0
Plantago	Plantains			1			1		1		0
Poa	Meadow-grass / tussock		1	1	1	1	1	1			3
Polygonum	Wireweeds / knotweeds		3	6							1
Portulaca	Purslanes			1	1						0
Ranunculus	Buttercups		1						1		0
Raphanus	Wild radishes		2	1			1		1		1
Rapistrum	Wild turnips / bastardcabbages		1								0
Rorippa	Yellow / mustard cresses		1								0
Rumex	Docks and sorrels		1	1							0
Senecio	Groundsels and ragworts		2	2	2						3
Setaria	Bristle grasses / foxtails	3	4	5				1			0
Silene	Campion / catchfly		1								0
Sinapis	Charlocks / wild mustards		2	1					1		0
Sisymbrium	Hedge mustards / rockets		2	1					1		1
Solanum	Nightshades		1	2		3					0
Soliva	Onehunga weed / burrweed								1		0
Sonchus	Sow thistles / puha		2	1			1		1		0
Spergula	Spurrey		1								0
Sporobolus	Ratstail / dropseeds										1
Stellaria	Chickweeds		1	1					1		0
Thlaspi	Penny cress		1								0
Tripleurospermum	Scentless mayweeds / chamomiles		1								0
Urtica	Nettles			1							0
Vicia	Vetches		1								0
Vulpia	Vulpia hair grass / silvergrass			1		1					0
Xanthium	Cocklebur / Bathurst and Noogoora burrs		1								1

Table.9. The top global, agricultural, weedy genera, containing three or more HR species, that are present in New Zealand, and the number of species in each genus, resistant globally to the main MoA groups. Sorted by the genera and MoA with the most HR plants. Derived from weedscience.org.

Genus	Common name	Mode of action code									
		B	C1	Other	A	G	O	C2	D	K1	F2
Amaranthus	Amaranths	9	10	8		4	3	2	1	1	2
Echinochloa	Barnyard grass	5	2	7	5	1	4	3		1	

Lolium	Ryegrasses	3	1	11	4	3		2	2	1	
Bromus	Brome grasses	6	1	0	4	3		1			
Conyza	Fleabanes	3	2	1		3	1	2	3		
Alopecurus	Foxtail grass	3	1	2	3			2	1	2	
Avena	Oats (wild oats)	3		7	3					1	
Setaria	Bristle grasses / foxtails	4	5	0	3					1	
Polygonum	Wireweeds / hnotweeds	3	6	1							
Poa	Meadow-grass / tussock	1	1	3		1		1	1	1	
Senecio	Groundsels and ragworts	2	2	3				2			
Digitaria	Summer grasses / crabgrass	1	1	0	4	1	1				
Eleusine	Goosegrasses / crowfoot grasses	1	1	2	1	1			1	1	
Phalaris	Phalaris / canary grasses	3	1	0	3			1			
Ambrosia	Ragweeds	2	1	1		2		1			
Chenopodium	Fat hen / goosefoots	1	4	0			1	1			
Cyperus	Sedges	6		0				1			
Chloris	Windmill grasses		1	0		4		1			
Hordeum	Barley grass	1		0	2	1			2		
Raphanus	Wild radishes	2	1	1		1	1				
Solanum	Nightshades	1	2	0					3		
Brassica	Brassicas	2	1	0		1	1				
Galium	Cleavers	3		0			2				
Sisymbrium	Hedge mustards / rockets	2	1	1			1				
Sonchus	Sow thistles / puha	2	1	0		1	1				
Carduus	Plumeless thistles			0		1	3				
Centaurea	Knapweeds / cornflower	1		0			3				
Lactuca	Wild lettuce	1		0		2	1				
Sinapis	Charlocks / wild mustards	2	1	0			1				
Apera	Silkybent grasses	1		0	1			1			
Epilobium	Willow weeds		2	0					1		
Euphorbia	Spurges	1		1				1			
Plantago	Plantains		1	0		1	1				
Stellaria	Chickweeds	1	1	0			1				

4.6.2. The role of the weed seedbank

One of the key features of weeds compared with other pests such as insects and fungi, is the weed seedbank, which is a kind of 'time machine' that sends weeds' genetic information, years, even decades, into the future. While it is possible to eliminate resistance from fungi, and particularly insects, by stopping all applications of the pesticide for sufficient time (e.g., ~7 years), this cannot work for weeds as the weed seedbank will transport the resistant genes through the non-use period, so when the herbicide is used again resistant weeds will already be present. So, once a HR weed has been created and it has entered the weed seedbank it is impossible to get rid of it.

It was once considered that the weed seedbank would act as a buffer, diluting the resistant genes in the population, and therefore weeds with a more persistent seedbank would be at less risk of resistance. However, there is very little evidence that has occurred in practice. Instead, weeds with long lived seedbanks are considered higher risk as their resistant genes can travel further into the future than those with short lived seedbanks.

4.7. Management risk factors for resistance

The third HR risk factor in Figure 11 is management practices. These are the aspects over which farmers clearly have a high level of control, and, therefore are the key drivers in successfully managing or enhancing the presence of HR plants on a given farm. The key management option to minimise resistance is to use a non-herbicide control method wherever possible and only when non-herbicide techniques are insufficient to achieve economically rational weed control, should herbicide use be considered. If herbicides have to be used, the following herbicide management practices will help to minimise the potential for resistance to develop.

4.7.1. Rotating and mixing modes of action (MoA)

The highest risk factor for creating HR plants is repeatedly using the same MoA, or worse, exactly the same herbicide product. This creates a very high evolutionary selection pressure as discussed in section 4.1. Repeated use of high and medium risk MoA (Figure 12) on high and medium risk plant families (Figure 13) is pretty much guaranteed to result in HR plants evolving.

MoA diversity is the solution, i.e., avoid repeatedly applying the same herbicide to the same paddock / area of land. Ideally a MoA should only be used on the same paddock / land once a year, and where more than one weed spray is required, then, a different MoA should be used, i.e., have a sequence of different MoAs.

4.7.2. Cross resistance

Where weeds have cross-resistance, avoid using MoA with known cross-resistance. Unfortunately easy to access and detailed information on which species are cross-resistant to which herbicides is limited. The following list of weeds with cross resistance, worldwide, that are also present in New Zealand are summarised from [19].

Mediterranean mustard (*Brassica tournefortii*), perennial ryegrass (*Lolium perenne*), annual ryegrass, (*Lolium rigidum*), hedge mustard (*Sisymbrium orientale*), sow thistle (*Sonchus oleraceus*), chickweed (*Stellaria media*), Noogoora bur (*Xanthium strumarium*) have cross resistance within Group A: Acetyl CoA carboxylase (ACCase) inhibitors, i.e., the fops, dims and dens. If a weed is resistant to a fop it is highly likely to also be resistant to dims and dens even if those herbicides had never been used on the weed population before.

Wild oat (*Avena fatua*), wild / sterile oat (*Avena sterilis*), Italian ryegrass (*Lolium multiflorum*), annual ryegrass (*Lolium rigidum*), green foxtail (*Setaria viridis*), have cross-resistance within group B the ALS inhibitors: the sulfonylureas, imidazolinones and triazolopyrimidines.

Red amaranth (*Amaranthus hybridus*), redroot amaranth / pigweed (*Amaranthus retroflexus*), common ragweed (*Ambrosia artemisiifolia*), field mustard (*Brassica campestris*), fat hen (*Chenopodium album*), broad-leaved fleabane (*Conyza bonariensis*), groundsel (*Senecio vulgaris*), are cross-resistant within group C 1,2 and 3, the photosystem II inhibitors, including: triazine, triazinone, uracil, pyridazinone and ureas.

Put simply if a weed is resistant to one herbicide in MoA groups A, B or C, assume, it is likely to be resistant, to all the other herbicides in that same group, and therefore use a different MoA.

There is potentially cross-resistance between groups G inhibition of EPSP synthase e.g., glyphosate and group H Inhibition of glutamine synthetase e.g., glufosinate-ammonium.

4.7.3. Rotating crops to rotate MoAs

Clearly, if genetically similar crops are being grown in rotation, e.g., the cereals, wheat, barley, oats, etc., it is much harder to diversify and rotate MoAs. Therefore having as diversified rotation as possible is a key means of having a diversified MoA sequence.

A more sophisticated approach is to choose crop sequences, such that, weeds that are hard to control with herbicides in the first crop, are then easy to effectively control with herbicides in the following crop and vice versa [9]. From a HR perspective, it would even better to not use herbicides that have only limited effectiveness in the one crop, and, to rely on the more effective herbicides in the other crop. Likewise, weeds that are hard to control in the following crop, should be vigorously targeted in the preceding crop. This is because herbicides that have lower levels of efficacy against particular weed species are more likely to have resistance develop against them. The researchers studying this approach found that it even achieved better weed management with less herbicide use - clearly a great outcome for both profit and minimising HR [9].

4.7.4. Recommended rates

There has been considerable discussion in the weed science community about optimum dose rates: known as 'the dose rate debate'.

For non-target site resistance, where resistance is due to the herbicide being prevented from reaching its biochemical target molecule, e.g., by denatured, translocated away, etc., which is often due to multiple genetic changes, where reduced doses are used, plants that have a 'weak' non-target resistance, will survive, where they would of died with a full dose, so those weeds will pass on their weak resistance to progeny where it is likely to evolve stronger forms. Full or higher dose rates would therefore be better for non-target site resistance.

For target site resistance, where resistance is due to a single change in the biochemical target molecule, which is often due to a small genetic change, the opposite is more likely, higher dose rates create a higher selection pressure due to the greater kill of susceptible plants, so therefore lower dose rates would be better - the opposite for non-target site resistance.

Therefore the recommendation is that the recommended rates be used, unless there is good evidence to do otherwise. It is also suggested that too much focus can be put on rates, and many other risk factors are more important.

4.7.5. Tank mixes

Using tank mixes with two or more different MoAs against the same weed species / genus is a key method of combating resistance. This is particularly the case where this prevents a single MoA being used repeatedly in sequence in the same paddock / land area. Tank mixes are also considered more effective at combating resistance than MoA sequences [5].

4.7.6. Non-crop areas

In New Zealand there is a considerable use of herbicides on non-crop areas such as fence lines, paddock margins, ditches, hedges, edges of driveways, etc. These areas are of major concern for the evolution of glyphosate resistant weeds in particular, due to the often exclusive use of glyphosate for weed control in these areas due to its low cost and broad spectrum efficacy. This is one of the most effective ways of generating resistance (section 4.7.1). Once HR weeds are created in non-crop areas their seeds easily spread into cropping areas creating major cropping problems. There are a range of options for addressing this issue which are described in section 7.

4.7.7. Monitoring for herbicide resistant on farm and actions to take

Prevention is better than cure: A diverse IWM strategy is key for both preventing HR weeds being created on farm and establishing if brought on farm. But, should HR weeds get a foothold either way, early detection is critical if effective management strategies are to be put in place. An effective HR weed monitoring strategy is therefore vital. A good strategy needs to include:

- Written records (see below);

- Information is recorded at the individual paddock level;
- Full details of every herbicide application;
- Always scout paddock (field walk) post herbicide application after sufficient time has elapsed that weeds should have died;
- Details of other non-chemical control methods;
- Scout paddock at key points in the season (e.g., establishment, mid crop, post harvest) and describe the general weediness, main species present, and especially anything unexpected - both from application issues and potential HR weeds.
- When undertaking field operations / tractor work also keep an eye out for weed issues - field operations often cover more ground more systematically than a field walk. If issues are suspected either stop and inspect or record location and return on foot post operation (when safe) to inspect.
- Review every paddock's cropping and weed history at the end of each season.

FAR's ProductionWise is ideal for recording this information.

When scouting fields or observing from the cab key indicators of HR weeds are:

- A gradual decline in weed control over several years;
- Healthy plants besides dead plants of the same species;
- Poor weed control leading to discrete patches;
- Poor control of one susceptible species when other, equally susceptible, species are well controlled [18].

These symptoms can be the result of other issues, e.g., poor spraying practices, so, it is important to be able to positively identify truly HR weeds. However, currently in New Zealand there are currently no services to confirm if a plant is HR. The MBIE funded "Managing Herbicide Resistance" project (started 2018) is aiming to develop tests. In the mean time, if the above indicators, point towards HR resistant weeds being present, consider them to actually be HR, then use all of the HR management strategies outlined in this handbook as part of an overall HR management strategy. Also contact FAR to discuss and obtain specific advice. Herbicide resistance can only be effectively managed if everyone works together at whole industry level.

For a newly identified or likely HR weed population in a paddock, the immediate action that should be taken include:

- For small patches of weeds (indicating a new HR weed establishment) manual removal or spot spraying (e.g., knapsack) with different MoA(s) to those used to date in that crop / paddock, and ideally a tank mix. If there are limited selective herbicides, consider, spraying out both crop and weeds, and hand sowing a competitive cover crop to fill the gap.
- If weed patches are larger, then, re-spray whole paddock with different MoAs including tank mixes.
- If the HR weed infestation is substantial consider writing the crop off, as the long-term economics of loosing the crop's income, but, getting on top of the HR weed problem, so it is less of an issue in future crops, may be more profitable.
- In all cases the HR weeds must be prevented from setting seed.

Longer term options include:

- Avoid using the MoA to which resistance is confirmed or suspected in the paddock, and potentially neighbouring paddocks, in the next few years.
- Choose crops for the paddock for the following years where:
    - Non-chemical weed management can be used with a high level of efficacy;

- Herbicides with a MoA which are highly effective at controlling the HR weed can be used (clearly needs to be different MoA to which the weeds are considered to be resistant) section 4.7.3;
- If the weed is considered to be restricted to one or a few paddocks, consider equipment hygiene, e.g., undertake paddock operations in these paddocks last, and then clean down equipment afterwards, to try to prevent resistant weeds escaping to the rest of the farm.

Accurate records mean that should HR weeds be suspected, the, paddocks herbicide history can be reviewed to look for possible causes, e.g., using a herbicide in the high resistance risk category. Records are also vital so that when a new seasons herbicide options for a paddock are being considered previous seasons herbicide applications can be reviewed to ensure their is sufficient rotation of MoAs. This kind of record keeping is also essential for quality assurance schemes such as NZ GAP. Again, FAR's ProductionWise has a range of features to help facilitate this including providing information on herbicides MoA's.

4.8. Best practice sprayer use

Best practice sprayer use is critical to get the most out of herbicides and all agrichemicals. Optimal sprayer use is a large and sophisticated topic in its own right. The GRDC in Australia has a comprehensive "Spray Application Manual" available from grdc.com.au/spray-application-manual in the form of 80 short videos on all aspects of spraying. The key points include:

- Confirming the weather is conducive for the chemicals to be applied and spraying in general;
- Confirming the correct pressure and nozzles for the job;
- Pre-filling checks with water only to ensure there are no leaks, nozzle valves are switching on and off and that all nozzles have an even and correct pattern, with no obvious signs of wear;
- Correct filling and mixing of chemicals and adjuvants in the tank;
- When spraying checking that flow and pressure are correct.

All sprayers should have an annual, monthly and every use list of checks and maintenance requirements. Your sprayer manual, supplier, and the GRDC manual listed above all provide this information.

4.9. Best practice herbicide management to minimise herbicide resistance

Integrated management approaches are focused on identifying if a problem exists and then picking the optimal solution, rather than just routine / calendar spraying. Therefore do not apply a herbicide just because you always used to put a herbicide on a given crop at that time. Monitor the crop for weeds: identify which species are present and actively decide if their populations are sufficiently large that the cost of control is lower than the likely economic loss due to the weeds (section 1.2). Identify the best herbicide for the crop-weed combination. Cross check that against the herbicides used in the last few years and avoid using the same MoA as previous applications. Also cross check against Table 8 to see if the proposed herbicide MoA has a high number of the weed species present in the paddock resistant to it globally and if so consider an alternative or a tank mix. Keep a record of the weeds that were identified and which herbicide(s) were used. Post application check the paddock to confirm that the herbicide application has been effective - see section 4.7.7.

Best practice herbicide management is about addressing the risk factors discussed in section 4.4. The most important practice is rotating herbicide MoA. Repeat application of the same MoA is one of the biggest risk factors for selecting HR weeds, so, rotating MoA is one of the most important means of preventing HR. This links with diversifying rotations, as diverse rotations allow for a wider range of MoAs to be used.

While there was initially a belief that pre-emergence herbicides would be more at risk of resistance due to prolonged exposure of weeds to the herbicides in the soil, this has not been borne out in practice and the recommendation is now that including pre-emergent herbicides, where possible, is best practice. Pre-emergence herbicides also reduces the population size of weeds that need to be controlled with post-emergence herbicides which are at greater risk of resistance developing. This is important as the likelihood of resistance developing is a 'numbers game' (section 4.1.1) so the smaller the population of weeds exposed to herbicides the lower the likelihood of resistance developing.

Use recommended rates. As discussed in section 4.7.4 both lower and higher rates are risk factors for selecting for HR. Therefore always use recommended rates unless you have specific advice from HR weed management experts.

Tank mixes using two different MoA are recommended, especially where the main herbicide has been used several times without a change, and/or where one of the MoAs has a large number of weeds resistant to it globally (see Table 8).

Optimising herbicide timing to get the best out of the different parts of the crop production cycle (Table 10)

Table 10. Factors to consider for optimised herbicide timing. From [3].

Herbicide timing	Aim	Mode of action	Advantages	Disadvantages
Pre-drilling	Encourage weed growth. Control weeds from harvest to drilling	Contact	Can use non-selective herbicides, which reduce resistance risk.	Early drilling shortens time for weeds to emerge and be controlled
At drilling	Apply before crop or weeds emerge, within 24–48 hours of drilling. Control weeds until end of winter	Residual	Prevents weed establishment. Essential building block of grass weed control; only effective timing for some species/herbicides. Limited resistance to pre-em herbicides	Poor weed control where seedbed quality is poor or seedbeds are dry. Crop seed depth, or soil cover, can be an issue with some herbicides
Autumn/ winter	Control later-germinating weeds or escapees from pre-emergence treatments. Target weeds when small	Residual Contact	Weeds visible to identify, which aids product choice	Control more difficult if weeds are large. Soils can be too wet. Stressed crops. Large crop canopies. Resistance problems common. Beware cold temperatures, which can reduce efficacy of some herbicides
Spring	Control spring-germinating weeds. Tidy up winter escapees	Contact Some residual	Weed spectrum visible	Large weed size. Sometimes too late for certain species. Target crop growth stage is missed
Pre-harvest	Control late-germinating and perennial weeds	Contact	Ideal timing for perennial weeds	Few species at correct growth stage. Some weed seed set. Some crop

				market restrictions

Use best spraying practices - see section 4.8.

Further information:

- A very substantial amount of herbicide resistance research has been done in Australian arable systems coupled with an extensive, industry wide, extension program. The entry point for the extension information is weedsmart.org.au.
- The Grains Research and Development Corporation (GRDC) grdc.com.au also has a wealth of information on IWM, herbicide resistance, herbicides, and spraying. A number of these are referenced in this booklet.
- One of these GRDC publications is a detailed technical document on herbicide mode of actions available from grdc.com.au/__data/assets/pdf_file/0027/293490/GRDC-GrowNotes-Herbicides.pdf This also includes information for each MoA on the effects of environmental conditions on activity and spray application as well as MOA specific spray application details including adjuvants and water quality. Note that Australia's group codes differ slightly from New Zealand group code. Always check the chemical family names when using Australian herbicide information.

5. DIY farm science

One of the profound properties of herbicides (and the other agrichemicals) is their ability to achieve the same outcomes pretty much regardless of where a farm is in the world, and what it's climate, soils and crops are. For example, if a herbicide kills a particular weed in a chemical companies research glasshouse, the same herbicide will kill that weed anywhere in the world. In comparison many physical and especially biological / ecological weed management techniques are highly context specific, e.g., the climate / weather, soil type, crop type, crop cultivar can all impact on their efficacy. This means that research on these solutions needs to be done under similar conditions to the farms using the techniques, and that the results may not be directly applicable to farms with different climates, soils, etc., i.e., the opposite of the highly generalisable results of the herbicide tests described above. This means that without unlimited research budgets it is impossible to undertake sufficient research to inform all farmers of the optimum IWM for their farm. Therefore farmers will need to do some of their own research to establish the best solutions for them.

Agronomic science can be highly complex and expensive, so, the expectation is not that farmers will undertake the full range of current science, rather, that they can trial straight forward changes and adaptation to their current farm systems and their impacts on weed management, for example:

- Trialling cover cropping and its many permutations;
- Testing a range of sowing rates;
- Trialling different row spacings or sowing arrangements;
- Comparisons of different cultivars for weed competition;
- Etc.

Many farmers have been doing exactly this very successfully for their whole careers, but, there is likely to be a need to do more in IWM systems. Where farmers are doing trials it is critical that they get the scientific methods sufficiently correct for the results to be reliable. The key points are:

- Replication;
- Randomisation;
- A control and/or current practice treatment;
- Representative measurement.

The key issue in agricultural science is that agriculture is naturally highly variable, mostly due to soils and weather, but, also from farming practices, e.g., sowing depth. The key to doing good DIY farm science is to ensure natural variation is accounted for, hence replication and randomisation. A control and/or current practice treatment is vital to determine if the new treatment is better or worse than the standard practice or doing nothing (the control). Representative measurement, is essential to make sure what matters is being measured, e.g., if grain yield is the key measure, eyeballing the crop and looking at height / biomass is not sufficient a measure. Yield, either via hand harvest of small plots or field scale using header yield monitors is vital.

Providing a full information on DIY farm science is outside the scope of this booklet, but, there are good resources available - some are listed below.

Further information:

- Understanding biostimulants, biofertilisers and on-farm trials bhu.org.nz/future-farming-centre/information/bulletin/2016-v1/understanding-biostimulants-and-biofertilisers [15];
- On-Farm Trial Guide - LandWISE landwise.org.nz/resources/publications/on-farm-trial-guide/

6. The integrated weed management (IWM) system

At a practical level integrated weed management means having all four toolboxes of physics, chemistry, biology and ecology open and using the best mixture of tools, i.e., the many 'little hammers', from all the toolboxes to manage weeds. This is both from the long-term and whole of farm techniques down to immediate specifics of a crop × weed combination in a specific paddock. Starting with whole-of-farm and long-term techniques are rotations.

6.1. Rotations

Writing in the 1938 Yearbook of Agriculture Clyde E. Leighty said:

> "Rotation of crops…is the most effective means yet devised for keeping land free of weeds. No other method of weed control, mechanical, chemical, or biological, is so economical or so easily practiced as a well-arranged sequence of tillage and cropping."[10]

Just before the dawn of herbicides, rotations were clearly considered a key part of weed management. Indeed it is only with the advent of the herbicides, the other pesticides, and synthetic nitrogen fertiliser, could agriculture simplify and reduce it's reliance on rotations [17]. Now that these technologies are under threat from evolved resistance and legislative restrictions, a key part of the solution is to reintroduce rotations and their key MoA: diversity. At its core many of the challenges faced by agriculture are due to a reduction in on-farm diversity, so a key part of the solution is to increase diversity once more: diversifying the range of crops and stock produced and diversifying the range of agrichemical MoA used.

Rotations are also not just important for weed management, nearly all aspects of production benefit from a well designed rotation: soil health, pest & disease (P&D) management, especially soil borne diseases, and farm & business resilience through diversified income streams. The trade offs are more complexity in the business and not being able to grow more of the most profitable crops. Rotation design needs to take all these factors into account.

For weed management, key factors to consider are:

- Varying spring and autumn sown crops - for cereal dominated system a swap of planting season can have substantial weed management benefits.
- Avoid having sequences of crops which are taxonomically similar, e.g., wheat, barley, oats, and, therefore have very similar herbicide MoA options. Try to have sequences with large taxonomic differences, e.g., grasses then broadleafs, and within broadleafs e.g., brassicas then potatoes, so that very different suites of herbicide MoAs can be used one year to the next, see also section 4.7.3.
- Include crops where mechanical weeding is highly effective, e.g., potatoes, interrow hoed cereals, so that some herbicides can be swapped for steel.
- Having a pasture phase. While this goes against the trend over the last decades of moving away from mixed farming and into separate livestock and arable specialisations, the benefits of a pasture phase in a cropping rotation for all aspects of the production system, soil, N fixation, nutrient losses, climate impacts, weeds, P&D, are substantial, and likewise, having a cropping break in a livestock enterprise is also highly valuable [17]. Innovative means to achieve this, rather than each farm becoming mixed, for example, livestock and cropping farmers working together in land sharing, can be considered.
- Rotational ploughing. Where grass weeds build up to intolerable levels in minimum tillage systems, rotational ploughing, e.g., once every 5+ years, resets the system, as the half-life of buried grass seeds is around three years (though some individual seeds can last for seven or more years) so there are few alive to be brought back up next time the plough is used.
- Varied rotations allow for different tillage and stubble management options (section 6.3).

- Where pre-emergent herbicides are used these will persist in the soil and may carry over into the next cropping period. The time between spraying and safely sowing a specific crop or pasture without residual herbicide effects (the plant-back period) can be as long as 36 months, depending on herbicide, environmental conditions and soil type.
- Maintain flexibility. If a paddock has a known weed problem, choose crops where the problematic weeds can be effectively controlled, both through herbicides (section 4.7.3) and mechanical weeding (section 6.5.1).
- Use cover crops / green manures where possible in-between crops to suppress weeds, and also protect soil, fix N, increase biodiversity etc., (section 6.2).

Further information

- FAR 'Grass 2 Crop' far.org.nz/assets/files/uploads/Iss_05_Grass_2_Crop.pdf
- FAR 'Non-inversion agronomy' far.org.nz/assets/files/uploads/Iss_01_Non_Inversion_Agronomy_May_09.pdf

6.2. Cover crops, living & dead mulches, undersowing and green manures

With the need to reduce herbicide use, often the first alternative considered is mechanical weeding, e.g., interrow hoes and tillage. However, over the last half century there has been a strong movement to reduce tillage due to the harm it does to soil, and, to keep crop residues on the paddock to further enhance soil protection. Therefore, tillage and mechanical weeding, while effective for weed management, can be a retrograde step for soil health. Cover crops and their associated techniques offer a 'third way' of replacing the chemistry of herbicides and physics of cultivation & mechanical weeding with biology and ecology in the form of cover crops. Not only is this better for soil - cover crops main purpose is for building soil health, but, using biology to fight biology and ecology to fight ecology means that evolution is on both sides of the ledger. If you pick a fight with evolution the only way to win is to have evolution on your side as well.

The terminology around cover crops is somewhat loose but the following are the main terms used:

- 'Cover crops' is one of two general overarching term used to refer to crops grown to cover and protect the soil, retain nutrients and build soil health.
- 'Non-cash crop' is the other broad term is , i.e., a crop grown for purposes other than generating 'cash' sales; its opposite is 'cash crop', i.e., crops grown for direct cash profit.
- 'Green manure' is mostly used to describe N fixing leguminous crops.
- 'Catch crop' is used to describe crops grown to 'catch' nutrients that would otherwise leach, i.e., principally nitrate nitrogen.
- 'Living mulch' is where a low growing plant is sown under a taller cash crop, with the aim of smothering out weeds, and often fixing N, dead mulch is where a high biomass cover crop is killed and the cash crop planted into the residue.
- 'Undersowing' is where the following crop (cash and non-cash) is sown under the proceeding crop (both cash and non-cash).

There are therefore a huge range of cover crop permutations. Most cover crop species are also regular cash crop and pasture species, sometimes some of the less common types.

Cover crops also have a key role to address issues such as legislation around nutrient loss to water, soil carbon levels and their links to climate change, and growing awareness of the importance of soil health, both on productivity and environmental issues. Cover crops are potentially therefore a win-win for soil health, weed management, nutrient losses, and overall farm resilience and profitability.

A key issue when selecting cover crops is to avoid species that will exacerbate cash crop pests and diseases, e.g., act as an alternative host, provide a green bridge, etc.

Cover crops are frequently grown as mixtures, to provide a range of benefits, such as increased biomass, better weed suppression, reduced P&D risks, increased nitrogen fixation and retention, etc. The most common mixtures are a cereal and a tall or climbing legume, but, there is increasing amounts of science that show highly diverse mixtures, e.g., >10 species from a wide range of plant families further boost the benefits of cover crops, especially around soil health and maximising biomass, e.g., see http://www.the-jena-experiment.de and youtu.be/j3SvG2nBCTM for examples of the ecological benefits of mixtures.

6.2.1. Filling in the gaps with cover crops

The simplest use of cover crops and green manures is to 'fill in the gaps' between cash crops. Where in the past soil would have been left fallow, cover crops should be used.

Fast growing species such as buckwheat (*Fagopyrum esculentum*), phacelia (*Phacelia tanacetifolia*) and mustard (*Brassica* and *Sinapis* species) are often used for short gaps, e.g., between harvest and sowing autumn sown cereals, while for longer growing periods, e.g., over winter, higher biomass species, such as cereals especially oats (*Avena sativa*), triticale (× *Triticosecale*) and ryecorn (*Secale cereale*) and legumes such as tick beans (*Vicia faba* var. minor) and vetch / tares (*Vicia* species) are grown.

The presence of a cover crop, short or long, inhibits weed seed germination (section 3.1.6) and completes with weeds that do emerge so reducing their ability to produce seed, and replenish the weed seedbank. Surviving weeds are also killed when the cover crop is terminated. If weeds have germinated but not seeded then this reduces the weed seedbank.

6.2.1.1. Termination, including crimper rollers

Termination of cover crops, including dead mulches (see below) can be done biologically, e.g., grazed with stock, physically, e.g., mown and shallow tilled, or chemically i.e., with herbicides. Ideally herbicide use would be avoided for termination, especially as the obvious choice of glyphosate is widely used in many other situations, so, putting it at increased risk of resistance due to repeated use (section 4.7.1). Physical termination also has issues, topper mowers leave the residue in strips and often can’t cope with the biomass. Mulcher / flail mowers need a lot of power / diesel and the matted residue can cause problems with drilling. Grazing with stock in comparison has two main benefits - often good fodder for the stock (though some cover crops can be toxic to stock e.g., vetch / tares), and the crop foliage is turned into urine and dung which provide mineral nitrogen to the soil, though some nutrients will be also be removed though stock growth. However, stock may not be available, it, may take them too long to eat if there is a large amount of biomass, and some cover crops are less palatable or have toxins.

One method of termination gaining a strong following in the Americas is using a crimper roller (called a roller crimper in the USA). This uses a purposed designed roller with protruding vanes to flatten and 'crimp' the cover crop (Figure 14).

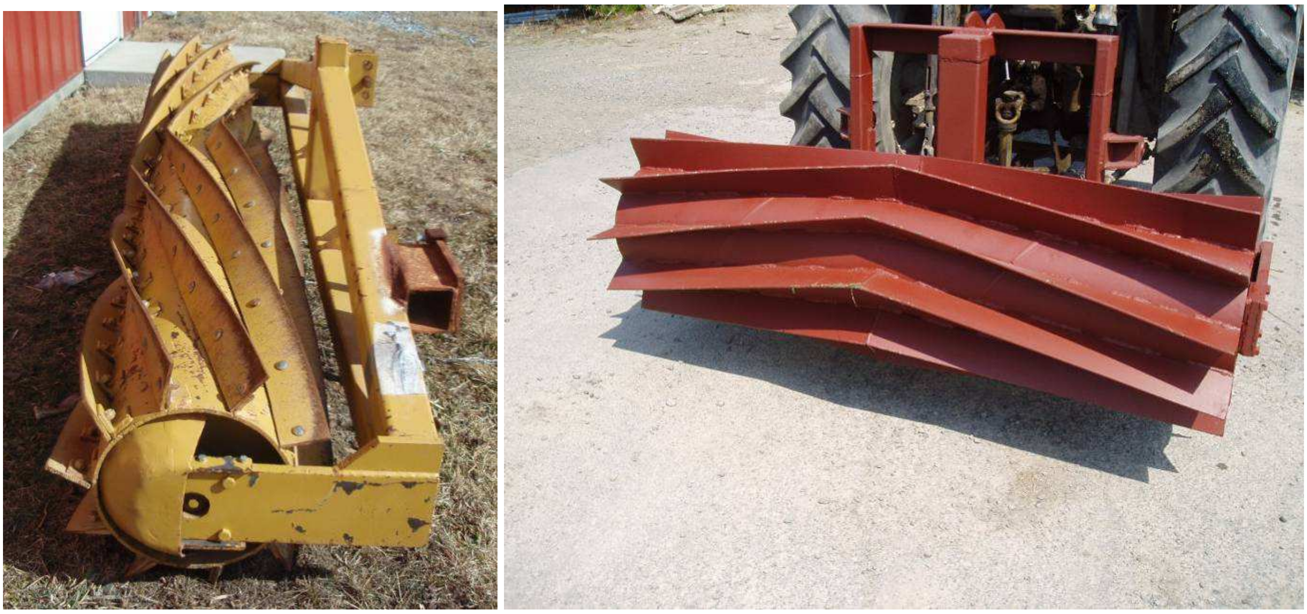


Figure 14. Helical blade crimper rollers.

Crimping causes plants to die, that would otherwise survive if only a smooth roller was used. The advantages of crimper rolling are:

- Dramatically lower fuel use than mowing and much fast work rates;
- Cover crop is laid on the soil as a weed suppressing mulch, unlike grazing off;
- It can be drilled through, but only with high residue drills in the same direction as rolling;
- Typically used with crimper roller front mounted and drill rear mounted; giving single pass turn around.

The key limitations of crimper rolling is that it only kills plants at full anthesis (flowering), partial flowering is not sufficient. This is a problem for spring sown crops in New Zealand as the main over-wintered cover crop species don't flower until early to mid summer, too late for planting of many cash crops. It is still often not 100% effective and may need additional herbicides to ensure 100% kill. Crimping also does not kill all cover crop species: many are highly resistant. Also many places in the USA that use crimping have very cold winters that kill most overwintering plants. Experiments in New Zealand found that pasture species that germinated in autumn from the weed seedbank along with the cover crops, grew through the mulch after it was crimped, i.e., they self-under sowed (see below). Despite these limitations, the considerable benefits of crimper rolling, and that crimper rollers are comparatively inexpensive, mean that it is a technique that is worth trialling to see if it can fit into NZ farm systems.

A variation on crimping has been developed in Europe where the vanes are sharpened so they cut rather than crimp the crop. This may kill cover crop species that crimping cannot kill, and also kill all species at earlier growth stages. However, there is currently no experience of using 'cutter rollers' in New Zealand, so this information is speculative. Cutter rollers also partly mix the residue rather than laying it in straight lines so it may be more of a challenge to drill into the residue.

Further information:

- Ted S Kornecki USDA crimping researcher ars.usda.gov/people-locations/person?person-id=3104;
- Rodale Institutes crimper roller page including links to CAD roller design plans rodaleinstitute.org/why-organic/organic-farming-practices/organic-no-till/;
- New Zealand research on crimper rolling merfield.com/research/2007/initial-trials-of-a-crimper-roller-in-new-zealand.pdf.
- Cutter rollers: Veenma 'Green Cutter' www.veenma.nl/green-cutter

6.2.2. Living and dead mulches

Although they have a similar MoA of a soil covering, and weed suppressing mulch, and are therefore grouped together, in practice, they are very different approaches.

6.2.3. Dead / residue mulches

Dead or residue mulches are similar to the retained residues in no-till systems. However, unlike no-till where the residues are from the previous crop, dead mulches are from a cover crop or green manure and have significantly greater biomass. For weed management the aim is to have sufficient thickness and longevity of the mulch to suppress weeds until the crop is able to suppress weeds itself. Drilling into this amount of biomass requires top end no-till drills, and/or the use of row-cleaners. Strip / zone tillage is also well matched to the use of dead mulches.

Seeding rates can be significantly higher than for cash crops, because cash crop seeding rates are based on the economic optimum seed multiplication rate, while for cover crops biomass is the objective, and increasing seeding rates, even double or triple can result in significant increases in biomass, though clearly at increased seed cost.

6.2.3.1. Allelopathy

A number of species, particularly oats, triticale, rye and brassicas such as mustard are well recognised as being strongly allelopathic (section 3.3.1), both when they are living and particularly as they start to decompose. This is beneficial when the allelochemicals suppress weed germination and growth, but, it is not beneficial when this occurs to a crop. Different plant species can respond very differently to the allelochemicals of the producing plant species, for example, wheat and rye allelochemicals will suppress wheat and oats but stimulate subterranean clover (*Trifolium subterraneum*) [4]. Newly terminated cover crops can produce considerable amounts of allelochemicals, with the levels declining after one to two weeks. Planting immediately post termination is therefore the most risky time for negative allelopathic effects.

6.2.3.2. Nitrogen lock up / robbery

Non leguminous cover crops, especially cereals, can take up significant amounts of mineral soil N (nitrate and ammonia) which is then 'locked up' in their residue until it decomposes. This ability is positive, in terms of reducing N leaching, especially over winter, but, if too much soil N is taken up there can be none left for the following cash crop, particularly in spring when mineralising of soil organic matter is very slow. This can result in the following cash crops suffering N starvation. Nitrogen fertiliser programs will have to be adjusted to ensure early season supply is sufficient. The soil nitrogen supply should be measured with nitrate quick test strips - see www.far.org.nz/articles/1231/quick-test-mass-balance-tool-user-guide for more information.

6.2.4. Living mulches

Living mulches are were a cash crop has a second plant species growing underneath it to provide weed suppression, and also potentially N fixation, and biological pest & disease management (through conservation biocontrol[2]). As they are living they supply season long cover unlike dead mulches which decompose over weeks to a few months. But, as they are living they also can complete with the cash crop, and if the balance is not right, they will reduce not increase yield. This makes living mulches more challenging to use until the right recipe is found. Typically low growing, and often creeping / spreading clovers are used, but, a wide range of plant species can be used, especially in bigger crops.

[2] en.wikipedia.org/wiki/Biological_pest_control#Conservation

There are two main approaches to establishing the crop in relation to the living mulch: pre and post crop establishment.

6.2.4.1. Post crop establishment of living mulch

Post crop establishment is the safer option: the crop is sown, grown for several weeks to give it a good head start, and, then the living mulch is undersown (see below) into the crop. This head start ensure the crop has the competitive advantage. In addition post emergent weed control in the crop, both physical and chemical can be used to eliminate the establishment weed flush, so, the living mulch can establish mostly weed free and therefore stay weed free.

6.2.4.2. Pre crop establishment of living mulch

Pre-crop establishment has more potential benefits but with higher, sometimes much higher risks. The benefits are that the living mulch can be established some time previously, e.g., in autumn so it protects the soil over winter, or, even, as a permanant cover crop, with multiple cash crops being planted into it. The risks are that the living mulch strongly outcompetes, even, kills the cash crop. The key to establishing into a pre-existing living mulch is to strongly suppress the mulch plant, e.g., through band spraying broad spectrum herbicides or using selectives that will check the mulch plants or strip / zone tillage.

6.2.4.3. Duel cash and living mulch establishment

It is also possible to sow both the cash crop and the living mulch at the same time - even with the same drill e.g., putting the two crops down different spouts. The key to this working is the cash crop being much quicker growing and competitive than the living mulch, otherwise as discussed above, the mulch will compete with the crop reducing yield.

6.2.4.4. Intercropping living mulches

A third route for living mulches is intercropping, which is where two or more crop species are grown in close proximity. With living mulches the cash and the cover crop are often sown in alternative rows, so, that competition between them is prevented till they have grown larger and the crop is more competitive, e.g., taller. With RTK GPS steering, the species can be sown at different times, e.g., the living mulch can be sown later. For wider spaced crops, such as maize, the intercrop can be sown over most of the interrow up to 10 cm from the crop row.

6.2.5. Undersowing

Undersowing is where the following crop is sown into the preceding crop, often not long after establishment, so the undersow is protected during establishment, and grows rapidly at harvest of the main crop. Undersowing is also used in New Zealand to renew pastures without terminating them. Undersowing differs from living mulches in that the undersow typically remains small and suppressed while the preceding crop is growing, while the living mulch needs to grow sufficiently vigorously that it inhibits weed seed germination and competes with weeds that do emerge.

The most common use of undersowing is sowing pasture under an arable crop, i.e., small seeded under larger seeded crops, but, larger seeded species can be undersown as well in the right conditions (see also relay cropping, section 6.4.10).

There are a number of considerable advantages to undersowing:

- It is a form of no-till, but without the drill and the need for chemical ploughing, i.e., knockdown / broad spectrum herbicides.
- It eliminates soil damage associated with the tillage that it replaces.
- Broadcasting seed or using a tine weeder has among the lowest tractor power requirements - saves diesel.

- It can represent a considerable saving in staff time and cost, particularly if it replaces a full round of tillage and drilling.
- It can shorten the inter-crop interval by weeks even months, as the undersow is already growing when the preceding crop is harvested, i.e., it has a head start, and, there is no delay due to spraying off or tillage and drilling (Figure 15).

Figure 15. Barley undersown with red clover. Left close to harvest, center, close-up of understory close to harvest, right, post harvest.

The key problem with undersowing is the undersown crop taking over main crop, either competing and reducing yield, or, complicating or preventing harvest, e.g. through too much green leafy material among cereal heads. A lesser problem is the undersow being out competed and killed, typically from being sown too late.

The key to successful undersowing is timing, timing, timing. However there is no overall recipe for optimum timing, it depends on crop species, both the main crop and the undersown crop, soil type, climate, weather, sowing rates, etc. For specific areas and crops, local undersowing recipes can be established through research trials (section 5), but, it is also simple for farmers to develop their own systems, starting with small areas (few square meters) done with a bucket and garden rake, through to 100s m^2 sown my machinery, till, confidence is gained to move up to paddock scale .

Typically seed is broadcast, and then needs to be incorporated into the soil, irrigation is one option, sowing before rain, another, and particularly effective is the spring tine weeder + pneumatic seeder combination (section 4521984.69233272.69174904.4521984) as the maximum seed throw from the seed outlets is around one meter, even multi-species mixtures with a wide range of seed sizes, and therefore ballistics, are applied evenly, and the tines then do both a final weeding and incorporate the seed.

Seed can also be drilled in, but, this is difficult at later crop stages as most drills are not designed to work in growing crops, and, accurate row placement may be important, in which case RTK GPS auto-steer is probably essential.

Further information:

- SARE Managing Cover Crops Profitably, 3rd Edition sare.org/Learning-Center/Books/Managing-Cover-Crops-Profitably-3rd-Edition
- FAR 2017 NCRS Research Summary book on Maize far.org.nz/files/display/7819/ncrs-web-spreads.pdf
- FAR 2016 NCRS Research Summary book on Maize far.org.nz/files/display/7820/41039-far-ncrs-book-2016-proof7-spreads.pdf
- FAR Soil quality under different maize production systems far.org.nz/assets/files/uploads/56_Mz_Soil_quality_under_different_maize_productions_systems.pdf
- DairyNZ-led collaboration Forages for Reduced Nitrate Leaching: Catch crops far.org.nz/assets/files/blog/files/f1f6b00f-b669-5ef0-8ecc-897f0da8deee.pdf

6.3. Cultivations and pre-crop establishment

Where cultivation / tillage is practiced, it can have a significant impact on weed management as it allows direct manipulation of the weed seedbank.

6.3.1. Stubble cultivation

Shallow cultivation, immediately after harvest, can stimulate weed seed germination, especially barren brome (*Bromus sterilis*), volunteer cereals and oil seed rape. For best effect, soil must be moist. However, cultivations prevent mammals and birds eating weed seeds, and also kill seed feeding invertebrates such as ground beetles. Stubble cultivation also directly reduces annual meadow-grass (*Poa annua*).

6.3.2. Primary cultivations

6.3.2.1. Plough

Ploughing is unique as it inverts soil, burying 95% of freshly shed seed to 15–20cm, but brings up 35% of old seed (Table 11). Subsequent cultivations are more shallow, so buried seed is not disturbed. Most weeds germinate from seeds shed in previous seasons. The effectiveness and optimum frequency of ploughing will depend on the longevity of the weed seed in the soil and will be most effective for species with short-lived seed, such as grasses including cereals.

6.3.2.2. Deep till and shallow till

Non-inversion tillage mixes the upper layer to a set depth (Table 11). Germinating weeds are a mix of newly shed seeds and those from previous seasons. About half the seed is buried below germination depth and 10 per cent of old seed returns to the surface.

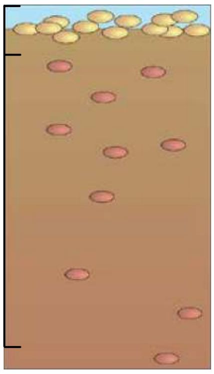
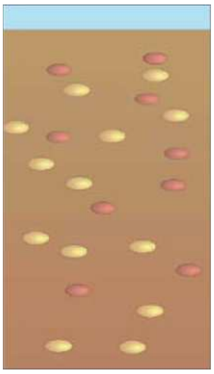
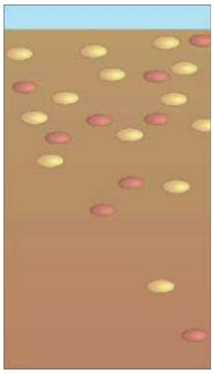
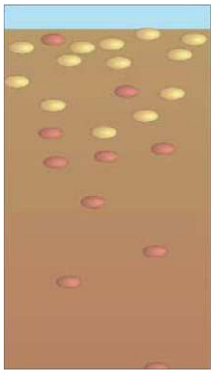
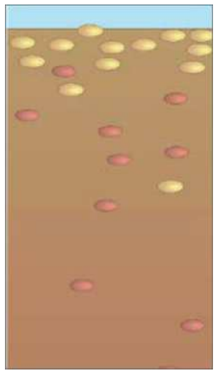
6.3.2.3. No-till

With no-till the soil is only cultivated by the drill. Weed seeds are predominantly in the top 3cm, but some smaller seeds move down soil cracks (Table 11).

6.3.2.4. Other

Subsoiling / deep ripping results in freshly shed seed falling down cracks but with little soil mixing. Using discs leads to more mixing – equivalent to deep or shallow till (Table 11).

Table 11. Cultivation options and effect on weed seedbank. From [3].

Cultivation	After harvest	Plough	Deep till	Shallow till	No-till
Soil movement	Not applicable	Inversion	Deep	Little	No mixing
Cultivations depth	Not applicable	Over 5cm, inverted	Over 5cm	Under 5cm	None
Example	Not applicable	Plough	Discs over 5cm	Discs under 5cm	No-till drill
		Many old seeds brought to surface, most new seeds buried	Fewer old seeds brought to surface, some new seeds buried	Very few old seeds brought to surface. Few seeds added to the seedbank	A few seeds may change layers
Soil depth 5 cm 30 cm					
Weed control		Generally reduces weed populations	Has little effect on weed populations	Keeps weed seeds in top 5cm of soil where they can germinate	Keeps weed seeds in top 5cm of soil where they can germinate

6.3.3. False and stale seedbeds

False and stale seedbeds are two highly effective ways to reduce in-crop weeds at establishment. The terms false and stale are often used interchangeably but they are used here to describe different but related techniques.

False and stale seedbeds are based on three properties of seedbanks:

- Most seeds in the seedbank are dormant;
- Cultivation / tillage is highly effective at causing non-dormant seeds to germinate;
- Most arable crop weeds can only emerge from the top five centimetres of soil, mostly half that.

As discussed in section 3.1.4 dormancy is what allows the seedbank to be persistent. That cultivation causes a flush of weeds is exceptionally well know to farmers and growers. However, that most weeds can only emerge from the top five centimetres of the soil is less understood. There is a direct physical (i.e., non-biological) relationship between the size of a seed and the maximum depth of soil the germinating plant can grow up though before it exhausts the energy or nutrients stored in the seed, and therefore dies of starvation Figure 16.

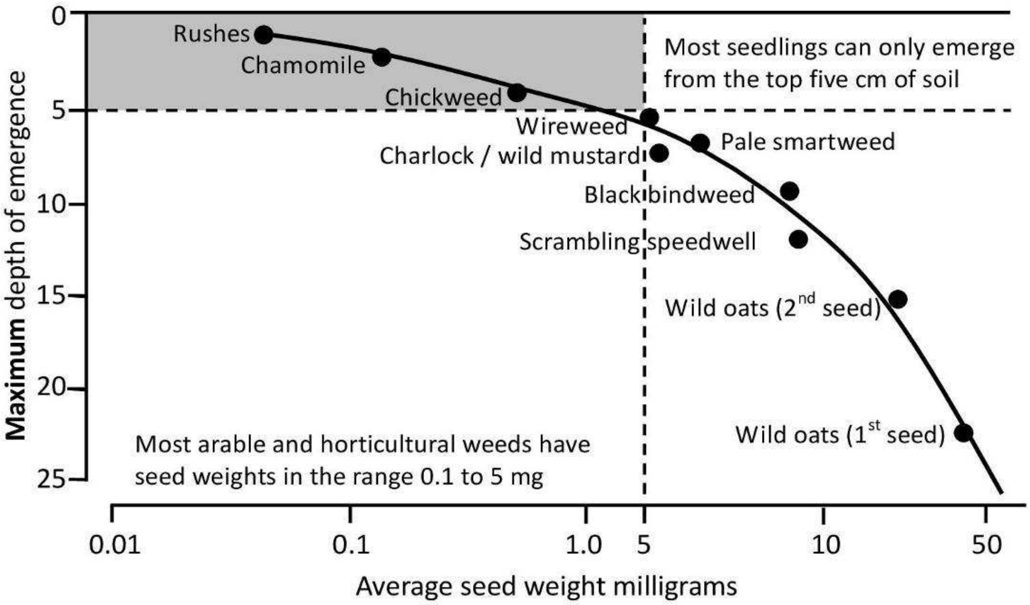


Figure 16. The maximum depth of weed seed emergence plotted against seed weight. Adapted from [21].

However, this is a maximum depth, which means only a few percent of seeds that size can emerge from that depth, the majority of them will emerge from much lesser depths. This means the majority of weeds that successfully emerge originated in about the top three centimetres of the soil.

False and stale seedbeds deplete the non-dormant 'emergable' seedbank in the top few centimetres of the soil just before or during crop establishment. This is achieve by using cultivation to encourage non-dormant weed seeds to germinate and then killing them with minimal or zero soil disturbance such that few additional seeds germinate. By diminishing the emergable seedbank at planting the number of weeds in the newly established crop can be dramatically reduced, and, as arable crops often achieve canopy closure quite quickly, and therefore achieve competitive advantage and inhibit further weed germination (section 3.1.6), the number of weeds in the crop can be considerably, even, dramatically, reduced.

However, like all other weed management techniques, false and stale seedbeds cannot control 100% of weeds. There is therefore an interaction between false and stale seedbeds and the size of the weed seedbank. If the seedbank is small and there has not been recent (last one to two years) weed seed rain then the numbers of new weed seeds germination after the false or stale seedbed will be small, e.g., a handful per square meter. If the seedbank is large and especially if there has been substantial weed seed rain in the last year producing seeds in a semi-dormant state (section 3.1.4), then repeated flushes of large even very large numbers of weedlings can be expected post treatment. Effective false and stale seedbeds require that the weed seedbank is small and particularly that there has been no major seed rain events in the last two years.

Both techniques start with the establishment of the seedbed ready for planting, except that planting is then delayed to allow the weed seeds to germinate. Although planting is delayed, it is essential that the seedbed is of the highest quality, i.e., good tilth and moisture, to encourage the largest possible weed flush.

6.3.3.1. False seedbed

In the false seedbed technique (Figure 17) sufficient time is allowed to elapse after seedbed preparation so that non-dormant weed seeds can germinate and emerge. Depending on the time of year / soil temperature and weed species this is typically between one and three weeks. Then, the emerged weeds are killed by very shallow re-cultivation / re-tillage, which also makes a new seedbed. False seedbeds therefore get their name because the first seedbed that was created is destroyed by the re-cultivation to kill the weedlings, and therefore is not the 'true' seedbed into which the crop is planted, but, a 'false' seedbed, the only purpose of which is to germinate weed seeds.

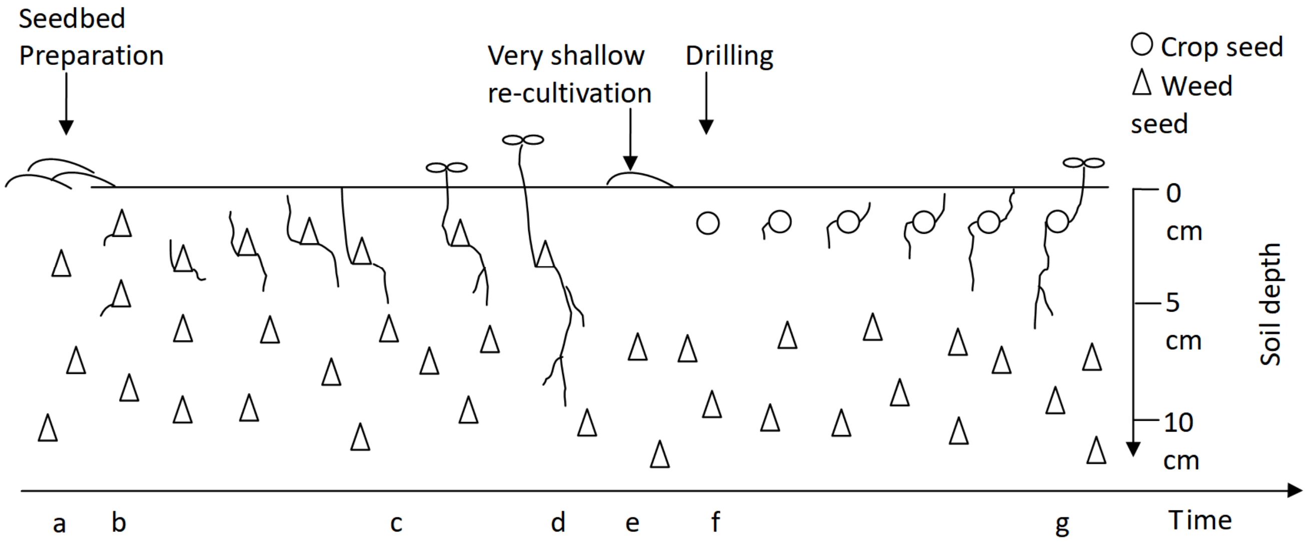


Figure 17. Illustrative scheme of a false seedbed: (a) seedbed is prepared , (b-c) non-dormant weed seeds in top 5 cm of soil germinate and then (c-d) emerge, (e) the soil is then re-cultivated with the minimum disturbance necessary to kill weed seedlings, (f) the crop is sown and germinates and (g) emerges into mostly weed free ground.

The re-cultivation is the utterly critical aspect of false seedbeds and the part that most people get wrong. If re-cultivation is too deep, it will bring up non-dormant seed from below the maximum emergence depth which will then emerge in the crop. It is therefore vital that re-cultivation is as shallow as possible, i.e., one to three centimetres, and, also achieves as high a kill of the weedlings as possible, ideally 100%.

There are however, few existing machines that can achieve this double requirement. The main off-the-shelf machine is the spring tine weeder. This can cultivate at the very shallow depths required, but, it often struggles to achieve 100% weed mortality. This can be maximised by making two passes of the weeder, e.g., in opposite directions or at 90° to each other. Beyond spring tine weeders a range of custom designed machines have been built. The simplest form is a 'roller undercutter' which has a very lightweight undercutter bar attached to a smooth roller [14], which while very effective suffers from the undercutter bar collecting field residue, so it is only practical in intensive market gardens with short runs of bed. The second approach uses A blade hoes mounted between two smooth rollers, which gives the most accurate and shallow depth control possible (< 2 cm) while minimising blockages and also coping with stones (Figure 18).

Figure 18. Twin roller and A blade hoe false seedbed tiller (left), rod weeder built into an S tine cultivator (right).

The third approach uses a 'rod weeder', typically attached to a smooth roller to enable accurate depth control, and also the roller firms up the seedbed, or as a rod integrated into a final pass cultivator, e.g., an S spring tine cultivator (Figure 18).

With their ability to be built to considerable widths, e.g., 10 m, and high forward speeds, especially of the A blade hoe design, work rates can be substantial, which coupled with their simple design and therefore low cost, and the ability to provide high, even exceptional, levels of weed control at the critical establishment period, false seedbed cultivators are an exceptionally valuable weed management tool that can give a substantial return on investment.

6.3.3.2. Stale seedbed

Stale seedbeds differ from false seedbeds in that the weeds are not killed by cultivation, but, either broad-spectrum herbicides (both contact and systemic) or thermal weeders. They are called 'stale' because the seeds are planted into the original seedbed (unlike false seedbeds) but the seedbed has become old or 'stale' at planting time.

As for false seedbeds, a quality seedbed is prepared, then planting is delayed to allow the weed seeds to start germinating, then the crop is drilled, and just before crop emergence (<24 hours) the weeds are killed so the crop emerges into weed free ground (Figure 19).

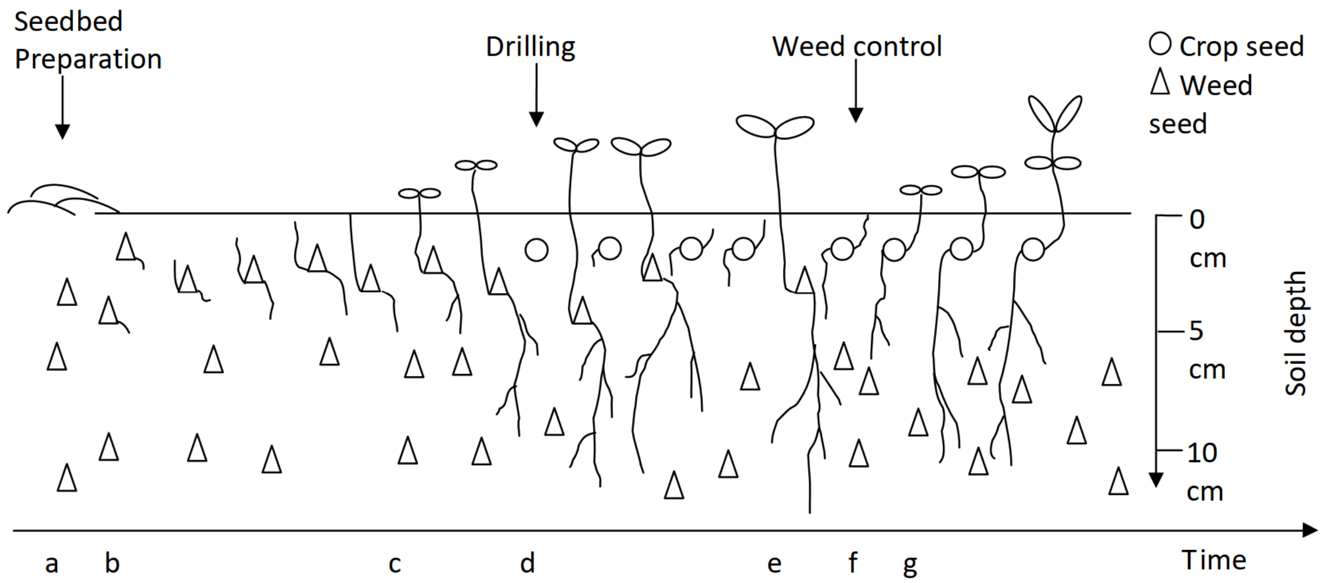


Figure 19. Illustrative scheme of a stale seed bed: (a) Seedbed is prepared, (b-c) non-dormant weed seeds in top 5 cm of soil germinate, (d) crop is sown, (c-e) weed seedlings emerge, (f) immediately prior to crop emergence weed seedlings are killed by herbicides or thermal weeding, (g) crop emerges into weed free ground.

The length of time between creating the seedbed and drilling depends on, time of year / soil temperature, weed species and the speed of crop germination. Typically sowing will be delayed one to two weeks, with longer delays when the soil is cold, with slow emerging weed species and fast emerging crops, and vice versa, shorter delays with warm soil, quick emerging weeds and slow emerging crops.

The critical aspect of stale seedbeds is timing, in that the weedlings should be killed as close to crop emergence as possible, e.g., 12 to 24 hours, so that the largest number of weeds are killed. Determining exactly when the crop will emerge can be challenging. If the seeds can be located in the soil, small amounts can be excavated to check on their growth. This allows for continual monitoring. Another technique is to used small pieces (a square meter or few) of horticultural 'frost cloth pinned down in the field. This warms the soil and accelerates emergence so that when the crop under the cloth starts to emerge the rest of the field is close behind. Both techniques can be used and are complimentary. The risk with stale seedbeds is weather or other factors (e.g., machinery availability) prevents the weed kill occurring at the right time and therefore the crop emerges into the weeds which may be a significant problem. Stale seedbeds are therefore a much higher risk approach than false seedbeds. It is possible to have an insurance weed kill part way through the process so if the final kill is missed there are not so many weeds in the crop.

While the aim of IWM is to minimise herbicide use, to minimise the evolution of HR weeds, using herbicides with the stale seedbed appears counter productive. However, as the crop has not emerged it is possible to use broad spectrum foliar herbicides that would damage or kill the crop, i.e., a different MoAs to those that used in-crop can be used, so allowing for MoAs rotation.

The non-chemical alternative of thermal weeding (e.g., flame or steam weeders) is not considered practical or economic in arable production, due to:

- The high capital cost of thermal weeders;
- Their only use is limited to stale seedbeds, so cost is not spread over a range of uses;
- Their often high running costs due to consuming large amounts of fuel;
- Flame weeders are a massive fire risk and prohibited during fire bans;
- Flame weeders use LPG as a fuel in large quantities, which is inconvenient compared with diesel.

Steam weeders do not pose a fire risk, and they (can) run on diesel, but, there are very few manufacturers, they are even more expensive than flame weeders, they use substantial amounts of water making them large and heavy and most are aimed at urban weed control or in perennial crops such as grapevines, so are unsuited to large-scale arable systems.

6.3.3.3. False vs. stale seedbeds

Research on false and stale seedbeds show that even shallow re-cultivation can encourage further weed seed germination compared with the non-soil disturbing techniques of stale seedbeds. As noted above, both techniques depend on good management of the weed seedbank, and where the weed seedbank is well controlled, the number of newly emerging weeds post re-cultivation will be very small, while a large and fresh weed seedbank will produce a considerable new flush of weeds post re-cultivation. One trial also demonstrated that the coulter on a vegetable seeder caused increased weed emergence post stale seedbed [2], which considering the amount of soil disturbance with narrower row, arable drills, a good false seedbed cultivator may well cause less soil disturbance than the drill.

Further information:

- False and Stale Seedbeds: The most effective non-chemical weed management tools for cropping and pasture establishment. bhu.org.nz/future-farming-centre/information/bulletin/2015-v4/false-and-stale-seedbeds-the-most-effective-non-chemical-weed-management-tools-for-cropping-and-pasture-establishment [14].

6.4. Crop establishment

Crop establishment is a critical time for IWM in arable crops due to many crops being able to strongly compete with weeds (section 3.3) if they are given the chance. The foundation for this is good crop emergence, so, all the usual requirements for good emergence need to be correct, these include:

- A healthy soil with good structure and soil organic matter levels;
- Good seedbed tilth in a cultivation / tillage system;
- Correct setup of drills (both tillage and no-till systems);
- Optimum soil temperature, i.e., not to cold, nor too hot;
- Optimum moisture levels;
- Correct sowing depth;
- Correct drilling fertiliser amounts, type, and placement;

These are of course all standard agronomic practices required for a good crop, but, they take on increased importance in an IWM system, and, where in the past in herbicide weed management systems it was possible to push the envelope, e.g., plant when its a bit too cold or wet, in IWM it is best to ensure that the crop has the very best start, as the chances of failure and a poor weedy crop are increased without increased herbicide use.

6.4.1. Rapid ground cover

There are also a range of other establishment practices, beyond the above standard requirements, that can provide significant levels of non-chemical weed management. Many of these are based on achieving rapid ground cover, because many weed seeds can detect the presence of existing plants which inhibits germination (section 3.1.6).

6.4.2. Sowing rates

Most sowing rates are based on the best seed multiplication economic return (i.e., number of seeds in vs. number of seeds out, per ha) in the absence of weeds. However, in an arable IWM system where crop competition is a key weed management tactic, increasing sowing rates can significantly increase the competitive ability of the crop and therefore reduce weed biomass and seed rain. Think of the increased seed cost as a replacement for another weed control activity. A secondary effect of increased sowing rates is that in many arable crops most of the small grain comes from secondary tillers and increased crop density reduces secondary tillers so more grain comes from primary tillers and is larger. However, increasing crop density can also increase the relative humidity in the crop and exacerbate some fungal diseases.

The impact of altering sowing rates on yield, economic return, weed management and disease pressure is often regionally specific due to differences in climate and soil. Experiments therefore need to be conducted locally, and, to date, there is limited New Zealand research available. On farm trials (section 5) will be required. Many of the other techniques described in this section have limited local research so on-farm experimentation will be required for them as well.

6.4.3. Drill / planter setup

As discussed in detail in section 6.5.1.6 interrow hoeing requires both precise and accurate setup of the drill so the interrow hoe can follow the drilled rows without damaging the crop while maximising weed control.

6.4.4. Fertiliser use and placement

To maximise yield, ideally the crop should get all the nutrients in applied fertiliser and the weeds get none. As most arable crops have larger seeds than most arable weeds and most weeds only emerge from the top two to three centimetres of soil (Figure 16 page 55) if fertiliser is band knifed below sowing depth then the crop roots are more likely to access the nutrients than the weeds, at least at early stages of growth. Conversely if fertiliser is broadcast and left on the surface, the smaller weeds with root systems at or close to the surface will have the first access to the nutrients as they are washed into the soil.

In addition, crop nutrient demands vary with growth stages, so, only applying fertiliser when the crop needs it, and is therefore most able to rapidly take it up, also ensures that weeds can access the least amount of fertiliser possible.

Making sure crops are optimally fertilised also means they will have the most vigorous growth and therefore be able to compete the most aggressively against weeds and better tolerate those that are present.

6.4.5. Crop species

Farming experience rapidly teaches that different arable crop species differ, often considerably, in their competitiveness against weeds. In IWM systems matching more competitive crops to paddocks with larger weed seedbanks and more competitive weeds, so that less competitive crops can be grown in the 'clean' paddocks, gains increased importance. Table 12 shows the difference in competitive ability of a range of arable crops against annual ryegrass (*Lolium rigidum*) in southern Australia.

Table 12. The relative competitive ability of a number of annual winter crop and the crop yield reduction (%) from 300 plants/m^2 of annual ryegrass (*Lolium rigidum*) at Wagga Wagga, New South Wales [11] from [24, page 61]. * rank = 1 most competitive to 7 least competitive.

Crop	Rank*	Yield reduction (%)
Oats	1	2-14
Cereal rye	2	14-20
Triticale	3	5-24
Oilseed rape	4	9-30
Spring wheat	5	22-40
Spring barley	6	10-55
Field pea	7	100
Narrow leafed lupin	7	100

6.4.6. Cultivars

There can also be a considerable difference in weed competitiveness and tolerance among different cultivars within crop species. A tolerant cultivar means than the crop can maintain yields even in the presence of significant weed biomass, while a low tolerance cultivar will loose a yield even when weed biomass is low.

In cereals it is well recognised that prostrate (horizontal) leaf types are more competitive than upright leaf types. This is particularly important at establishment as prostrate leaf types achieve faster ground cover thereby suppressing weed seed germination. Older taller cultivars are also more competitive and/or tolerant than newer dwarf cultivars. However, there can be a considerable variation in a cultivars competitive ability between years and locations, indicating that there are multiple factors involved. Therefore, and as for cultivar comparison trials for yield, experiments testing competitiveness need to be undertaken in representative locations over multiple years. New Zealand specific data is limited at present, so, on-farm trials (section 5) will be important to build up experience, while field experiment sites build up more comprehensive data, particularly linking crop traits and genetics to weed competitiveness and tolerance.

6.4.7. Row spacings and arrangements

Row spacings and arrangements can have a major impact on crop yield and weed management, but, with the dominance of herbicide based weed management, there has been limited focus on row spacings for weed management. However, row spacings and arrangements have a critical role to play in IWM - both for physical and biological / ecological control approaches

6.4.7.1. Physical implications for row spacings and arrangements

At the whole farm level the decision whether to use contiguous and/or incontiguous mechanical weeders (section 6.5.1.4) is the key determinant of row spacings and arrangements. If interrow hoes are to be used then crop rows have to be in parallel rows (e.g., not in a checkerboard or random layout) and as many crops as possible need to be grown on the same interrow /crop row spacings, as adjusting interrow hoes is time consuming and their use is time critical.

Before the advent of computer guided hoes the minimum row spacing it was practical to weed was around 20 cm and more typically it was 30 cm, but with computer guidance row spacings of 15 cm and even 10 cm can be hoed, though with narrower rows the greater the amount of unhoed intrarow soil there is, i.e., the wider the crop rows the greater the area of paddock surface that is hoed (Table 19, page 79).

There are multiple trade offs with different row spacings. Fundamentally, and all other factors being equal, narrower row spacings, that mean crop plants are planted more on the square (equidistant) than on rectangular spacings increases the competitive ability of the crop, through better ground cover and earlier canopy closure as the distance between rows the crop needs to cover is smaller. Yield is also theoretically maximised with rectangular spacing, though most arable crops can still achieve full yields on quite rectangular spacings. However, wider rows allow for a greater area of the paddock surface to be interrow hoed leaving a smaller unweeded intrarow (Table 19). In addition, as crop population per hectare remain (mostly) the same regardless of row spacing, wider rows mean more crop seed per length of row, which makes the crop more competitive in the immediate intrarow area, which has fewer mechanical weeding options. Also, where a spring tine weeder is used in interrowed crops, the higher crop density in the rows, associated with wider row spacings, can force the tines out of the crop row and help protect the crop.

Row spacing also impacts stubble handling at planting, i.e., wider rows permit the use of row cleaners, and wider rows also can increase fertiliser placement options, e.g., deep banding.

Wider rows are likely to be required for techniques such as inter-planting, undersowing and relay-cropping (section 6.2). Where the secondary crop is going to be drilled, wider row spacing is required for the drill to pass, and even with broadcast undersowings very narrow rows may create too much competition and therefore smother out the undersow.

6.4.7.2. Biological / ecological implications for row spacings and arrangements

Where only contiguous weeders are being used in a crop a range of additional approaches can be used.

Very narrow crop row spacings, e.g., < 10 cm permit even faster canopy closure and increase crop competitiveness, but, there are obvious practical limitations around what minimum spacing any given drill design can achieve, and the cost of adapting or purchasing new seed drills.

A much cheaper and more practical option, is to use double sowing where the crop is sown twice at right angles to each other, or at a minimum of 45° where right angles are impractical (e.g., due to headland configuration). Again, target population per ha should be maintained, so, half the seed rate for each sowing should be used. This technique, is again, aimed at early canopy closure and therefore increased crop competitiveness.

6.4.7.3. Row orientation

Research in Australia has shown that the competitiveness of cereal crops is increased by planting in an east–west rather than a north–south direction as east–west more effectively shades weeds in the interrow than north–south direction rows [24, p70]. The effect is greater the closer to the poles as even in summer the sun is at an angle rather than overhead so there is shading of the interrow. At New Zealand's latitude, the effect should work equally well if not better than Australia. However, the technique does not work in broadleaf crops for a range of reasons. Likewise, the technique is more effective against grass than broadleaf weeds. In low weed populations the benefits may be small. At sunrise and sunset the tractor will be driving directly at the sun in one direction blinding the operator, though autosteer can help address this issues. And unlike Australia where large expansive farms permit crop rows to run in any direction, in New Zealand, topography and paddock shape and size often are the main determinant of planting orientation.

6.4.8. Drilling dates - autumn vs. spring

Sowing at the optimum time of year (soil temperatures, day length etc.) for each species and cultivar is important to achieve optimum crop growth which will give the greatest competitive effect against the weeds. More importantly rotating between autumn and spring sown crops has been shown in numerous studies to provide significant amounts of weed control, as many arable weeds are either spring or autumn germinating, and even where they can germinate at both times of year, germination rates are frequently much lower in the 'off' season, and, weed plants often fail to set as many viable seeds in their off season.

6.4.9. Crop mixtures

Crop mixtures are where two or more different crop species, and also cultivars of the same crop, are grown together. It is also called multiple cropping, intercropping, plant-teams and polyculture. New Zealand's white clover and perennial ryegrass pasture mixture is the classic example of this technique. As in clover and ryegrass the agronomic benefits of crop mixtures can be profound. The underpinning ecological science is 'symbiosis' where there are mutually beneficial interactions between the species, and, also increased ecological diversity. As an example, farmers in the UK have achieved a 73% reduction in weed biomass in a wheat winter bean (*Vicia faba*) mixture compared to monoculture beans [1]. Crop mixtures are also not just of benefit for weed management; the benefits in terms of pest & disease control, overall yield, crop quality, preventing lodging etc., can be as valuable, if not more than for weed control. Crop mixtures are therefore considered to have very substantial potential benefits.

However, there are clearly complications with using crop mixtures. The best performing mixtures often contain plants from very different taxonomic families, often a grass and a broadleaf. This puts considerable restrictions on herbicide options, particularly foliar selectives. It also restricts insecticide and fungicide options. The weed, pest & disease benefits of the mixtures therefore need to more than compensate for the reduced agrichemical options.

The crops need to have closely similar harvest dates and also be harvestable together. The seeds / grains also have to be sufficiently different that they can be efficiently separated during seed cleaning, and the seed cleaning systems and companies need to be able to cope with two or more lines of cash seeds coming out of one bulk lot. For certified seed crops, certification rules may prohibit crop mixtures.

While international research and farmer experience has shown multiple benefits of crop mixtures, like many ecological techniques, the results are often site specific, so, overseas experience can only be taken as a starting point, and, on farm experimentation (section 5) will be essential.

Further information:

- DIVERSify: Designing InnoVative plant teams for Ecosystem Resilience and agricultural Sustainability www.plant-teams.eu

6.4.10. Relay cropping

Relay cropping is where the following cash crop is planted into the previous cash crop often shortly before harvest with the aims of eliminating the inter-crop period, especially cultivation, and advancing the date of harvest. This compares with mixed cropping where both crops are planted and harvested at the same time.

While there are many benefits from relay cropping, there are a number of technical requirements to get it to work well. If residual herbicides are used in the previous crop the following crop must be able to tolerate them. Typically the following crop rows are planted between the preceding crop rows - so being able to accurately drill is vital, so RTK GPS is likely to be essential. The drill / planter for the following crop needs to be able to work in the preceding crop. Where the following crop is drilled not long after the preceding crop is drilled this is less of an issues, but, where the following crop is to be drilled close to harvest of the previous crop, this is much more of an issue. Late planted relay crops therefore tends to be used with wider spaced crops such as maize. The harvest of the preceding crop must not damage the following crop unduly, so tough flexible crops such as cereals work well, brittle crops such as beans don't. Like undersowing there is potential for the following crop to compete too much with the preceding crop, though this reduces the closer to the harvest date of the preceding crop, that the following crop is planted. Pesticide compatibility: the crops need to be able to have the same agrichemicals applied to them for pest control when both are present. For herbicides, if the preceding crop has been well weeded, then, there should be little need for herbicides for the following crop as the shade from the preceding crop should suppress weeds, and without cultivation there is little to encourage new weed seeds to germinate. Band spraying (section 6.5.3) is also an option. The same is not true of fungicides and insecticides, and, for the main insects and fungal diseases of both crops, chemical options that can be applied to both are required and that also have appropriate harvest intervals. As for crop mixtures, the increased diversity may help with pest and disease control. The crops may have different nutrient needs, especially if one is close to harvest and the other just establishing; banding of fertiliser may therefore be required.

6.4.11. Herbicides

The key herbicide decisions at establishment are whether to use a pre-emergent herbicide. There is a strong recommendation to use pre-emergent herbicides where possible as they have a lower risk of resistance developing and they reduce the size of weed populations exposed to post-emergent herbicides (section 4.9).

6.5. Post crop emergence

6.5.1. Mechanical weed control

Mechanical weed control can be considered the S group MoA - S for steel. The good news is mechanical weeding has not been standing still during the herbicide era, dramatic improvements and entirely new types of machinery (S MoA sub groups) have been developed over the last fifty years, such that it is possible to achieve excellent weed management in large-scale arable crops entirely without herbicides. The ongoing invention and development of entirely new mechanical weed control MoAs, such as CombCut and Aerostar-Rotation, is in clear contrast to the lack of new herbicide MoAs. While the chemical toolbox thins out the physical tool box continues to fill up.

6.5.1.1. How mechanical weeders kill weeds.

There are three methods by which soil engaging, mechanical weeders kill weeds:

- Uprooting;
- Severing or breaking;
- Burial.

Different weeders implement these three methods at different levels of effectiveness. The way different weeders implement the three methods, and how that interacts with a weeds physical attributes (e.g., size, morphology, (section 3.4)), and environmental conditions (e.g., hot & dry, vs. cold & wet), determine the weeds mortality rate / how effective the weeder is. There are clearly a large number of variables at play, and mastering some of the machines can require a fair amount of time and knowledge. If you don't get perfect results first time, do not therefore write the machines off, persevere.

6.5.1.2. Crop size or weed size?

For many herbicides, timing of application is often dependent on crop growth stage, especially for over-the-top selectives. In mechanical weeding, weed size is (nearly) everything. The very best time to weed is when the weeds are at cotyledon stage. For each extra pair of true leaves (dicots) or true leaf (monocots) the weeds produce, the effectiveness of mechanical weeding lessens exponentially.

Some people advocate weeding mechanically at the 'white thread stage' i.e., post germination but pre-emergence. However, when weeds that have germinated but not emerged and are buried under more soil they can often continue growing through the extra soil, and therefore survive. This indicates that for weeders that include burial as a means of killing weeds, which is many of them, weeding at the white thread stage may result in lower weed kills that at cotyledon stage. There is however no known research undertaking such a comparison for any weeder.

6.5.1.3. Environmental operating windows

Environmental operating windows are the weather and soil conditions within which different weeding technologies can successfully and safely operate (Table 13).

Table 13. The different environmental operating windows of mechanical and herbicide weed management.

Operating Window	Mechanical	Herbicides
Soil conditions	Works best in dry, conditions, wet conditions will stop some weeders working.	Mostly unaffected by soil conditions except for residual herbicides.
Wind	The windier the better - aids desiccation.	Above 10 kph increased risk of drift and 20 kph maximum.
Rain	Weed desiccation, is non-existent, most machines negatively effected, a small number can still however work well in the rain.	Can’t spray in the rain. Speed of rain fastness varies.
Temperature/ humidity	Hotter and drying the better, aids desiccation. Cooler temperatures see reducing weed kill.	To hot or cold unsuitable, low RH evaporation risk.
Bees	Not toxic to bees. Presence of bees not an issue, a few may be physically killed.	Can be toxic to bees. Care needed.

Mechanical weeding and spraying are therefore highly complimentary in their operating windows. The key conditions that stop spraying, i.e., winds over 20 kph are highly beneficial for mechanical weeding as it aids desiccation. Likewise, conditions that dramatically reduce the effectiveness of mechanical weeding, i.e., wet soils, are much less of an issue for herbicides. Having both mechanical and spray options available therefore gives farmers a considerably increased overall weeding operation window.

6.5.1.4. Broadacre / contiguous vs. interrow / incontiguous

Mechanical weeders come in two broad categories:

- Contiguous weeders that weed the whole paddock surface aka 'broad-acre';
- Incontiguous weeders, that only weed in-between crop rows, e.g., interrow hoes.

Contiguous weeders can be used both in crops sown in rows (of any width) and continual crop cover, e.g., pasture. As the weeding action is applied to both crop and weeds, the crop needs to be sufficiently robust to survive the weeding action which kills the weeds. This typically means larger seeded crops such as cereals, peas, beans, etc., that produce larger more robust seedlings.

Incontiguous weeders have aggressive weeding tools, e.g., horizontal blades, that kill everything, even larger weeds. The crop is spared as their are gaps (hence incontiguous) between the weeding tools that allow the crop safe passage through the weeder. These can only be used on crops grown in clearly defined rows, but, with computer guidance systems (section 6.5.1.6) much narrower row spacings, e.g., down to 10 cm, can be weeded, with some caveats than with manual steering.

6.5.1.5. Contiguous weeders

There are four main contiguous weeders suitable for arable crops, spring tine weeders, Einbock Aerostar-Rotation, spoon weeders (aka rotary hoe) and Combcut®. Like herbicides, they each have different MoA so each has strengths and weaknesses, and in a large part they compliment each other, so, having more than one would be beneficial.

Spring tine weeders

Spring tine weeders, also called spring tine harrow, finger weeder, and many other names, were developed in the 1950s. They are a highly versatile tools, that beside weeding can also be used for final tillage passes, re-cultivating false seedbeds (section 6.3.3) and can be fitted with a pneumatic seeder to broadcast and incorporate seeds (section 6.2.3).

Spring tine weeders consist of a large number of round spring steel tines, between 5 to 8 mm in diameter, that rake through the soil, uprooting, breaking, and burying weeds (Figure 20). Like S spring tine cultivators, the tines are mounted in multiple rows, to achieve good ground coverage without blocking, and, the rows of tines are mounted on modular 'wishbone' units that allow the tines to follow the paddock contour (Figure 20). The ends of the tines are normally angled, up to a maximum of 90°, with 45° the most common and lesser angles and even straight tines available (Figure 20). Larger angles make the ends of the tines point more forward so they dig into the soil more and are more aggressive, lower angles are less aggressive, but, they also pick up less residue. Large angle tines will act as giant rakes if there is much residue in the paddock.

Figure 20. The modular 'wishbone' unit (left) also showing pneumatic seeder outlets, and, 90°, 45° and 15° tine angles (right three photos).

As the design is modular, a wide range of widths are available (Figure 21), up to 27 m for semi mounted versions. In the right conditions high forward speeds (10-20 kph) are possible so work rates can be substantial.

Figure 21. Large spring tine weeder, folded (left) extended (right) with pneumatic seeder attachment.

There are a considerable number of manufacturers so there is a large amount of choice of designs and options.

Table 14 is a standard table, used for listing the key properties of each of the weeders outlined in this handbook, to allow for easy comparison among the different weeders.

Table 14. Spring tine weeder properties table.

Mode of action	Uprooting, breaking and burial.
Adjustments	Increasing forward angle of the tines, increased downward pressure, and faster forward speed increases aggressiveness. A few manufacturers are now putting remote tine angles adjustment on machines, and a few are using sensors to adjust the tine angles on the fly as soil conditions vary.
Crops	Arable monocots and many arable dicots, e.g., cereals, maize, beans, linseed, potatoes. It can also be used in harder leaved transplanted crops with care and more vigorously after they are well anchored. Plants need to be able to recover from some inevitable leaf damage.
Crop size	Monocots can be weeded from emergence through to larger plants e.g., 30 cm, although greater care is required in young plants and for larger plants speed has to be reduced to prevent plants catching and wrapping around tines. With longer tines, quite large plants, e.g., 40 cm can be weeded with care. Dicots, especially smaller seeded species, may be quite susceptible at small growth stages. When weeding recently emerged crops cultivation depth must be less than sowing depth. Dicots, because of their branching and spreading habits catch on the tines more easily resulting in them being ripped out, so weeding them beyond 10 to 15 cm high, depending on species, can be challenging.
Impact on crop	Inevitably damages some crop foliage and may pull out some crops plants, though susceptibility varies considerable between species and growth stages. Crops must therefore be robust enough to tolerate treatment and be able to recover.
Weed types	Annuals, more effective against dicots than monocots. Ineffective against established perennial weeds with the exception that it can be used to rake shallow creeping weeds , e.g., Elymus repens, out of paddocks after initial cultivations.
Weed size	Weeds must be small to be effectively controlled, typically cotyledon to two true leaves. Effectiveness declines very rapidly with increasing weed size so the cotyledon stage should be targeted.

Soil type	Works best in free flowing soils such as sands and loams, less effective on soils that can dry hard such as silts and clays unless there is a good tilth.
Soil tilth	Needs a fine crumbly tilth, will not penetrate hard soil or soil cap.
Stones	Undamaged by stones. However, its effectiveness will decrease as the number and size of stones increases as they reduce the amount of soil that the tines disturb and hence the percentage of weeds it kills.
Soil moisture	Limited effectiveness in wet soil, medium dry soil is best, also ineffective in soils dried hard.
Weather	At least dry and warm, ideally hot sunny and/or windy conditions. Overcast and damp/wet weather will significantly reduce weed mortality.
Plant residues	Larger angle tines (e.g., >45°) need essentially residue free paddocks as the forward angle of the tine tips are very effective at collecting plant material, especially pieces of more than a few centimetres in length. Lower tine angles which point backwards when in use are much less prone to collecting residues as the tines lift over the residues if they start to build up.
Work rate	Potentially very high due to large widths and high forward speeds (10-20 kph) which are limited by tractor stability and damage to crop.

An example of the level of weed control that can be achieved with a spring tine weeder is Figure 22 which shows a transplanted carrot (steckling) seed crop. Carrots are transplanted at finger size, into 60 cm rows and 30 cm apart down the row, and are only just anchored in the soil, which is a worse case scenario. The photo shows the edge of the cropped area with the plough furrow on the left and an area of very weedy soil the weeder could not reach, with a clear line where the weeder has weeded, with carrot stecklings visible. The soil is a very stony Lismore. This is a significant challenge for a tine weeder, due to the widely spaced and poorly rooted nature of the crop, with leaves that can be pulled by the tines, the very stony soil, and the exceptional weed burden. Despite this, a very large proportion of the weeds have been controlled only using a spring tine weeder, by going slowly (~2 kph), tines set back, at low pressure, and, repeated passes in contrary directions.

Figure 22. Example of the potential weed control achievable with a spring tine weeder in the worse possible crop and highly challenging soil in terms of the amount of stones.

Further information

- Michigan State University, Department of Horticulture, extension video on spring tine weeders youtube.com/watch?v=X57zjHNuBeE

Einböck, Aerostar-Rotation

The Aerostar-Rotation is a proprietary machine developed by Einböck GmbH & CoKG (Figure 23). Einböck describe it as a hybrid between a spring tine weeder and spoon weeder / rotary hoe (see below), in that it has thin round steel tines raking through the soil like a spring tine weeder but, on a rotating wheel like the spoon weeder (the weeding action is however not like a spoon weeder).

Figure 23. Einböck, Aerostar-Rotation. Photos courtesy Einböck GmbH & CoKG.

As the machine is relatively new, and, there is limited experience of using the machine in New Zealand the following information is tentative.

The weeding action is more aggressive than the tine weeder as the tines are being pushed into the soil, and the speed of raking is not just due to forward speed but also the rotation of the tines. More soil is moved than a spring tine weeder, the spiked wheels have an effect akin to a star-wheel hay rake, where a wave of soil is moved laterally.

Table 15. Einböck Aerostar-Rotation properties table.

Mode of action	Burial, uprooting and breaking.
Adjustments	Increased downward pressure, and particularly faster forward speed increases aggressiveness.
Crops	Arable monocots and some arable dicots, e.g., cereals, maize, beans, linseed. It also appears to be able to be used in some transplanted crops at slow(er) speeds.
Crop size	Monocots can be treated at any size, although care is required in young plants, and larger plants weeded at speed will suffer significant leaf shredding. Dicots, especially smaller seeded species, will be susceptible at small stages, in a large part due to burial. Larger sized monocots can also be weeded, though speed must be reduced or leaves will be shredded. Maximum plant size is around 20 cm high which matches the tine length.
Impact on crop	Inevitably damages some crop foliage and may pull out some crops plants, though susceptibility varies considerably between species and growth stages. Crops must therefore be robust enough to tolerate treatment and recover.
Weed types	Not fully established. Small shallow rooted weeds, both monocots and dicots likely to be effectively killed. Weeds rooted below the cultivation depth, particularly dicots will be more resistant. Unlikely to have much impact on perennial weeds, though, it may shred foliage.
Weed size	Weeds ideally need to be small to be effectively controlled, typically cotyledon to two true leaves. Effectiveness declines very rapidly with increasing weed size so the cotyledon stage should be targeted.
Soil type	Works across a range of soil textures, as it has a more aggressive action than the spring tine weeder, especially as the tines are punched nearly vertically into the soil, so it can work in harder soils.
Soil tilth	As it is more aggressive that a spring tine weeder, and the tines are pushed into the soil, it can work on courser tilths, and break soil clods up more than a spring tine weeder.
Stones	Small stones, e.g., < 5 cm are considered less problematic, but the effect of larger stones is unknown, they may start to force the spiked wheels to ride over them and therefore exit the soil. With the star-wheel hay raking action, it may also start to move stones bigger than 5 cm sideways in significant amounts, i.e., start to work like a stone rake.
Soil moisture	Yes to be demonstrated, but, it may be more effective in wetter soils than spring tine weeder. Dryer soils will give better results as more weeds will die from desiccation and be unable to re-root.
Weather	Dry and warm, ideally hot sunny and/or windy conditions. Overcast and damp/wet weather will likely reduce weed mortality.
Plant residues	Einböck claim that it will work in high residue soils, but, that is likely to be high residue by European farming standards, not, American no-till residue levels. Unlike tine weeders, especially with tine angles above 45°, which will collect residues, the straight tines and rotation means that residue tends to fall off or be thrown off the tines depending on speed. However, where there is a continual cover of residue it may well clog up on the wheels, and like, a star-wheeled hay rake it may move residue sideways, potentially all the way across the width of the machine.
Work rate	Potentially high due to large widths, but, higher forward speeds, e.g., > 8 kph, are likely to result in crop shredding, which, may have a significant direct impact on yield and also open plants up to disease.

Spoon weeders / rotary hoe

The spoon weeder, is called a rotary hoe in North America, which is where it is mostly found, i.e., it is uncommon in Europe. It consists of a number of spoked wheels, with each spoke having a flattened, angled ends i.e., the spoons (Figure 24). These enter the soil vertically but exit about 45° so flicking soil and weeds up into the air. The wheels run in two banks to improve ground coverage, and, there are high residue designs with a larger gap between the two banks of wheels and cleaning knives to force residue off the spokes. For best effect it needs to be used at high speeds, e.g. > 10 kph to get sufficient soil shatter and throw into the air. It does not have as high a level of ground coverage due to the gaps between the wheels as the spring tine weeder and Aerostar-Rotation. It therefore relies on high speeds depths to achieve good soil shatter and throw. Weeds thrown into the air and separate from soil have a much higher air resistance than the soil crumbs so end up on top of the loose soil and desiccate. It is the only soil engaging, contiguous weeders, that is designed to work in residue.

Figure 24. Spoon weeder / rotary hoe. Top, European model (photo courtesy Einböck GmbH & CoKG), bottom left, USA high residue model, bottom right spoon tips.

Table 16. Spoon weeder / rotary hoe, properties table.

Mode of action	Burial and uprooting with some bending / breaking of stems.
Adjustments	Lowering the toolbar increases downward pressure on the wheels which increases penetration depth and therefore aggressiveness. Higher forward speed increases the height that the soil is thrown and therefore aggressiveness but tends to reduce soil penetration. High speed, e.g., > 10 kph are required for effective working.
Crops	Arable crops, particularly cereals, maize, some dicots, mainly larger and deeper seeded species.
Crop size	Monocots can be weeded at all growth stages, but carefully at emergence, dicots are susceptible at seedling stage, need to have first true leaves out. Can be used pre-emergence. Able to weed plants up to 15 cm tall.
Impact on crop	If plants are too small they will be flicked out, and also damaged by soil rain. Larger plants mostly pass through with limited direct interaction with the spoons, but, where there is high residue levels plants may be flattened by falling debris.
Weed types	Annual monocots and dicots.
Weed size	Cotyledon stage to two true leaves maximum. The spoon weeder is ineffective against weeds with four true leaves (dicots) two true leaves (monocots). No effect on perennials.
Soil type	Wide range of soil types from sands to clays, as it aggressively punches the spoons into the soil.
Soil tilth	Spoon weeders are highly effective at breaking up soil crusts / caps, and have significantly improved emergence of crops trapped under such caps. If the tilth is too fine, the soil will flow off the spoons rather than be thrown up in the air, so will reduce efficacy. It's best when the weeder breaks the soil up as it is working.
Stones	Spoon weeders and stones do not mix as they accelerate the wear of the spoon tips, and more than a small amount of stones will reduce penetration and therefore the amount of soil picked up by the spoons. If spoons are worn efficacy is significantly reduced.
Soil moisture	Soils need to be at moisture levels that allow soils to fracture into a fine tilth with minimum force. If soils are too wet they will deform, i.e., the spoons will just punch holes in the ground, and if to dry they will break into clods not a fine tilth. This is more of a problem in clay soils.
Weather	Dry and warm, ideally hot sunny and/or windy conditions. A large cloud of soil and crop residue is created, so, in fine soils considerable amounts of dust can be created.
Climate	Due to limited weed size window and the need for good desiccating weather conditions it is less suited to climates with unpredictable wet weather.
Plant residues	Handles crop residues well. There are high residue models are available where the wheels are spaced further apart to prevent residues collecting between them, bearing protectors and static knives to cut residue off the as the wheels turn.
Work rate	Potentially large due to large working widths, e.g., 12 meters and high forward speeds of 10 to 20 km/h.

CombCut

The CombCut was invented in the early 2000s by Jonas Carlsson a Swedish organic farmer and is now sold by LyckeGård Group AB, in Sweden. It is quite different to the previous three weeders which are all soil engaging and designed to be used on small weeds. In contrast, CombCut is non-soil engaging, and designed to selectively remove larger broadleaf weeds from mostly grass / cereal crops from weeks to months post emergence. It works by a horizontal bank of dagger like knives that allow thin flexible crop plants to pass through while cutting off thicker stemmed and more rigid weeds, and has rotating brushes to push the crop and weeds through the knives (Figure 25). It can be used in all cereals, pasture, linseed, and maize and onions when small.

Figure 25. CombCut showing whole machine (top) weeds being cut (bottom left) adjustable knives (bottom right). Photos courtesy of LyckeGård Group AB.

Combcut is therefore unique in managing weeds in established crops. While it mostly does not kill the weeds, it, 'resets' the competition between crop and weeds, setting the weeds back significantly so the crop gets the upper hand. It may therefore need to be used more than once if weed regrow too much, to maintain the competitive advantage of the crop. It also can be used to cut off flower heads and therefore prevent weed seed rain, which includes using it above crop height, in which position it can be used for 'rouging' in any crop as it is no longer combing through the crop but surfing over the top of the crop.

As it is non-soil engaging, it is unaffected by soil moisture content - as long as the paddock is not so wet that tractor access is impossible. It can also be used in, and is mostly unaffected by, wet and windy weather, unlike most soil engaging mechanical weeders, it can even be used while it is raining. It has very low power requirements - only the forward force to cut the weeds and power the rotating brushes. It is best used front mounted, as it can’t cut weeds that have been flattened by the tractor wheels, but, it can be both front and rear mounted.

Table 17. CombCut properties table.

Mode of action	Cutting off above ground foliage and stems.
Adjustments	Forward speed, top link length / pitch angle, knife height from the ground, knife tilt and angle (set on the machine), brush vertical and horizontal position relative to knives plus brush rotation speed, can all be altered.
Crops	When used to comb through the crop only thin flexible crops such as cereals and linseed. When used above the crop, any crop.

Crop size	Variable: as the crop grows, especially when entering BBCH stage 3 (stem elongation) the height of the knives needs to be increased. When used above crop height, any size / height crop can be weeded.
Impact on crop	If correctly setup and used at an appropriate height for the crop growth stage, there is no impact on the crop. If used incorrectly crop could be completely cut off.
Weed types	When used to comb through the crop, mostly broadleaf weeds, though it has been used on blackgrass (*Alopecurus myosuroides*). The weeds need to be thicker or more stiff than the crop. If used above the crop, even thin weeds such as wild oat (Avena fatua) can be cut.
Weed size	Larger weeds. Weeds need to be sufficiently high for the knives to be able to reach down to them. Weeds need to be sufficiently thick for the knives to cut them.
Soil type	As combcut is non-soil engaging it is unaffected by soil type.
Soil tilth	As combcut is non-soil engaging it is unaffected by soil tilth.
Stones	Very large protruding rocks (uncommon in New Zealand) can damage the knives and there is an automatic rock avoiding system to protect the knives.
Soil moisture	As combcut is non-soil engaging it is unaffected by soil moisture, unless paddocks are so wet that tractor access is impeded.
Weather	Unaffected by weather, as it is non-soil engaging, and as the weeds are completely cut through, cut foliage is unable to regrow. It can be used in the rain, though wet weeds may require higher levels of brushing to pass through the knives. Also unaffected by wind.
Climate	Any climate. Developed in Sweden and widely used in cooler wetter Scandinavian climates.
Plant residues	As combcut is non-soil engaging it is unaffected by soil plant residues on the soil surface, although, if the knives are run into very thick residues it is likely they will clog.
Work rate	High work rates are possible with current maximum width of 9 meters and forward speeds of 8 to 15 kph though it has been used up to 22 kph. However, some weed / crop combinations require much slower forward speeds, e.g., 5 kph, to achieve good weed control and particularly avoid crop damage.

6.5.1.6. Incontiguous weeders

Incontiguous weeders have gaps for the crop to pass safely through as the weeding action is generally highly aggressive and will kill any plant. In arable crops the dominant type is the modular, parallelogram, interrow hoe, though the name is now slightly incongruous, as they are increasingly used as platforms for a range of both interrow and intrarow weeding tools. There are now forty plus manufacturers of interrow hoes, mostly European, so there is a wide range of designs to choose from. However, the key technological advance that has revolutionised interrow hoes is computer guidance systems.

Computer guidance systems

Before the advent of computer guidance systems, interrow hoeing was a technology most farmers chose to avoid unless they had to use it, e.g., organic farmers, as the guidance options were to have a person sitting on the hoe manually steering it, doubling labour requirements, or, by mounting on a specialist toolcarrier tractor, which were expensive, and required exceptional steering skills. Computer guidance / steering systems have revolutionised interrow hoeing turning it into a standard, three point linkage operation, with accuracy and speeds far beyond what a human could achieve. There are two main approaches to computer guidance: vision and GPS.

Computer vision systems use a digital cameral to continually feed images into a dedicated computer system that determines the locations of the rows in real time, and then guides the hoe to keep it on the crop rows. GPS systems have to use Real-Time Kinematic (RTK) full autosteer systems as only these have sufficient accuracy. The basic approach is to just use the tractor's steering, the advanced approach is to have independent steering systems on both the tractor and also the implement - called 'implement steering' or 'double-steer'. There are some critical aspects to understand for both systems, and, often contrasting limits to their abilities.

To state the obvious, vision systems need something to see to guide the hoe, so they are unable to work if the crop had not emerged or the row location is obscured, e.g., rain has caused the crop to bend over. GPS system are totally blind to the crop rows, all they can 'see' is the satellite A-B line, so they can work whether the crop is up, or not, or obscured, or even not yet planted! However, vision systems can cope with real-world variability, e.g., bent rows, or rows planted with a hand-steered tractor, and they have higher accuracy than even RTK GPS double-steer due to the time it take for corrections signals to travel between the base station and tractor. If GPS is being used on the hoe, it has to also be used to drill the crop, i.e., the crop rows and the A-B line have to match perfectly. That means that if all tractors used for sowing and hoeing must have their GPS systems compatible and using the same A-B line.

GPS double-steer, works by having separate GPS antenna on the tractor and the weeder, with a system that allows the machinery to be steered independently of the tractor, typically a hydraulic side shift between the three point linkage and the machine, or, soil engaging steering disks. The latter are mostly used for the original purpose of double-steer, working sideways on slopes and with contour cropping. For interrow hoeing the side sift is preferable, because it allows the hoe to lock over the crop rows while it is still lifted on the three point linkage. This overcomes one of the major irritations of using tractor only steering, in that it can take several short runs up and reversing back down the tramlines, at the start of the row to get the tractor accurately on the A-B line from the beginning. With side-shift, double-steer, the tractor can still be on it's run-in arc as it turns into the row, but, the hoe, drill, or other row following machinery, is positioned directly over the row by the side shift, allowing the machinery to be put down, even if the tractor is not yet fully on the A-B line. Some farmers consider this to be almost as big a game changer as GPS was over manually steering. Disk steering clearly can’t do this as the machine needs to be on the ground for the steering wheels to work. With very large hoes the sideways thrust of the hoe can also push the tractor sideways, in which situations, stabilising disks are used on the side shift to oppose the lateral forces.

The other advantage of double-steer is even greater accuracy. While tractor autosteer produces very straight rows, double-steer produces exceptionally straight rows and exceptionally accurate placement, such, that it is possible to have bout overlaps, e.g., a three meter seed drill, sows in two passes, but a six meter interrow hoe then hoes both drill bouts, something that is impossible with tractor steer, at least without much wider crop gaps which is undesirable (section 6.4.7).

Double-steer is only available from a small number of GPS autosteer suppliers. The hydraulic side shift system between the three point linkage and the machine can also cause issues, it moves the implement away from the tractor often by 20 to 30 cm, which for large implements will increase the leverage on the tractor significantly. The side shift can also get in the way of PTO connections, and, for some machines where the three point linkage is recessed the side-shift can impinge on parts of the implement. There are also a considerable range of designs for the side shift system, the most common is like a forklift side shift, the other main design uses a parallelogram, and there are a range of pros and cons for each.

It is also possible to mix and match GPS and vision systems, for example a standard, tractor autosteer system is used to drill the crop, and then a vision system is used to hoe the crop, either on a handsteer or autosteer tractor.

There are also other guidance systems, e.g., ground wheels steered of the top link with slack lower link arm stabilisers, 'wand sensor' systems, both mechanical and electronic, where the wand slides along stout crop plants, e.g., in maize, 'furrow followers' were a V furrow is put in the ground at drilling, and with ridge crops like potatoes the ridges can be used, often with guide wheels. These can be highly effective but often lack accuracy, reliability, and ease of use and with the advent of computer vision and RTK GPS they have mostly been supplanted, especially for larger scale operations.

Interrow hoes

Interrow hoe designs are now dominated by the modular parallelogram design (described below) with a few alternative approaches such as the brush hoe, and basket weeder. The modular parallelogram design (Figure 26) is considered an optimal solution as all manufacturers have coalesced on this approach and there are now over forty manufacturers. While still called an interrow hoe, modern machines are now more of a platform on which to mount a wide range of weeding tools, both interrow and intrarow.

Figure 26. Modular parallelogram units of an interrow hoe.

The parallelogram units consist of the parallelogram itself, an adjustable semi-pneumatic depth wheel and toolframe, on which the weeding tools are mounted. This arrangement allows the toolframe to follow ground contours very accurately while also keeping the toolframe parallel to the ground so that accurate weeding tool depth is maintained. The parallelogram units are attached to a toolbar which allows a variable range of widths, from tractor width up to the current maximum of 25 meters.

While the modular parallelogram design is now universal, the configuration of the components is highly variable, with individual manufacturers even offering a range of designs to suit different crops, e.g., narrow units for cereals, and wide, high clearance units for maize. There are a lot of desing parameters to consider when choosing a hoe such as:

- Do the units match crop row spacings and also wheeling positions?
- Are the clamps attaching the parallelogram units to the toolbar one-side type or does the attachment system wrap around the toolbar, and if so, what mounting positions of the units are impossible due to items (e.g., three point linkage) on the front of the toolbar?
- Are there enough mounting points on the toolframes for all the weeding tools required for different crops, and so that soil and residue flow from forward weeding tools is not impacting following tools?
- How easy is everything to adjust, especially frequently adjusted items such as the depth wheel and weeding tool depths?

- Is there good lateral rigidity of the parallelogram, i.e., very little side to side movement of the toolframes? This is critical to stop the toolframe wobbling side to side and therefore reducing the lateral accuracy of weeding tool placement;
- How are the weeding tools mounted on the toolframe?
    - Are the clamps proprietary or generic?
    - Are there spring clamp options so tools can vibrate to aid weeding?
    - How fine / accurate is the horizontal adjustment of weeding tools?
    - Is horizontal and vertical adjustment of weeding tools locked by a single bolt, or, are do they have separate locking mechanisms (better)?
- How long is the unit, is it compact or widely spaced? This can be critical for headland turning;
- What is the down-weighting system of the parallelogram? Springs, weights, or hydraulic / pneumatic?
- What range of weeding tools does the manufacturer have?
- How easy is it from the cab to see most of the weeding tools when they are in the soil, so blockages etc., can be seen?
- Are crop protection disks or shields required?
- How easy is it to lock the units in the lifted position for transport?

There are clearly a substantial number of factors to consider in choosing an interrow hoe, so, it is recommended to get good advise, from experts and farmers already using interrow hoes.

Weeding tools

There is a large variety of weeding tools, both interrow and intrarow that can be used on modern interrow hoes. The main weeding tools are horizontal knives, designed to cut the weeds in half as close to the hypocotyl as possible (section 3.4.3) These come in three main formats L, A and T blade hoes, named after their shapes (Figure 27).

Figure 27. The three main types of horizontal knife blade hoes L blade (left) A blade (middle) T blade (right)

A hoe blade may appear to be simple, but, there is a considerable amount to design a good hoe blade. Figure 28 shows the key parameters:

- Rake angle (α) is the lift angle of the hoe blade from the horizontal. A low rake angle creates a cleaner cut, with little soil movement, while larger rake angles moves more soil along the blade and also greater mixing. Too little rake angle and the blade with scrub on the soil, i.e., the whole bottom of the blade contacts the soil, rather than just the cutting face.
- Sweep angle (γ) is the blade angle perpendicular to travel direction. Sweep angle is a trade off between self-cleaning, effective cutting and draught force. If the sweep angle is too small then the blade will not self clean, and there is less of a slicing action in cutting the weeds. As sweep angle increases blades length has to increase to cover the same row width. Optimum sweep angle is around 60°.

- Pitch (ρ) only applies to A blades. Typically an A hoe blade will sit flat, e.g., as in Figure 27, and have no pitch angle, which limits its ability to penetrate hard soil, but means it maintains the same cutting depth across it's whole width. In comparison, cultivator points, e.g., a duckfoot have the point lower than the rest of the body so it digs in.

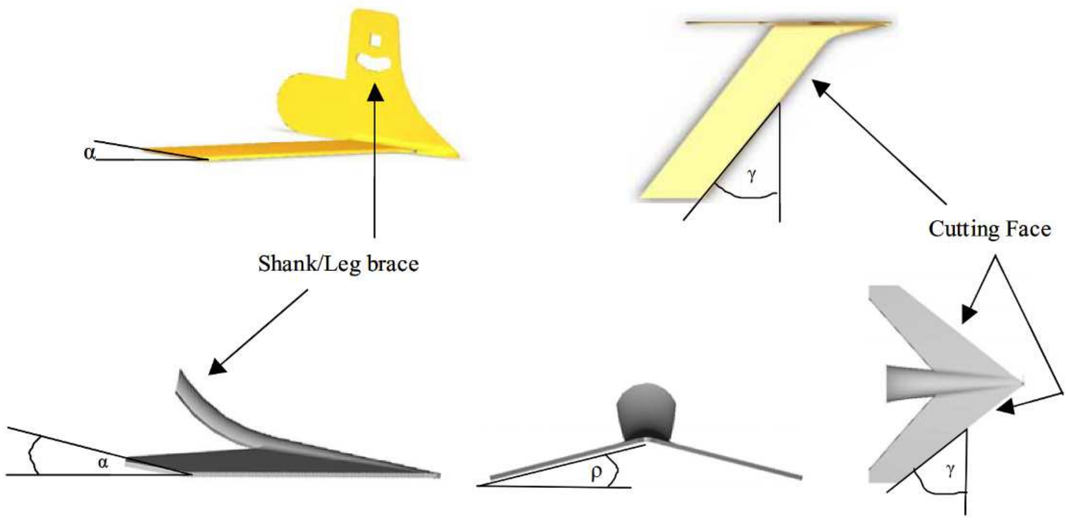


Figure 28. Hoe blade classification. α = rake angle, γ = sweep angle, ρ = pitch. From [27].

L blade hoes come in a wide range of designs which have considerable variation in their efficacy, and also if they are designed for lower or higher speed use. Beyond the sweep and rake angles, contrasting the L blade hoes in Figures 27 & 29 the front points are either 'cut-up' or 'cut down'. Cut-up tends to result in residue and weeds catching on the leg, while cut-down cuts through residue and larger weeds keeping the leg clean. The hoes also differ in the heal, which is the back of the vertical side of the hoe, both hoes in Figure 27 have no heal, so soil flows into the crop row potentially burying the crop, while Figure 29 has a large heal which curves away from the crop row preventing soil spilling into the row.

Figure 29. L blade hoe with down-cut front point, and a large 'heal' to push soil away from crop row.

L blade hoes are typically used in pairs either side of the crop row, and were the dominate blade design for use in vegetables. A blade hoes are typically used down the center of the interrow and are not used close to the crop as soil flowing off the ends of the blades can bury small crop plants. T hoes are much less common, but have been revived by the arrival of computer guidance systems. They are used the same as L blade hoes, in pairs for weeding right next to the crop row. Their advantage over L blade hoes is that as the crop grows in size (particularly for vegetables) the blades don't need to be moved outwards so much as the leg is not next to the crop and the blade can slide under the foliage where an L blade would cut / rip foliage. The issue with T hoes is the point is hidden by the soil so operators can’t see where it is, to steer by as is done with L hoes, but, this is not an issue for computer guided hoes.

When working with small crop plants, crop shields, both rotating disks and swinging flat plates are available to stop soil burying the crop.

A range of other weeding tools are available, including cultivator points (like duckfoots) to help break up hard soil and mini spring tine weeders post blades to further break up weeded soil and increase weed kill.

Table 18 gives the properties of interrow hoes as a comparison with the four contiguous weeder (section 6.5.1.5) however, as it is not the interrow hoe itself that does the weeding but the weeding tools attached to the hoe, and there are a large range of weeding tools, Table 18 is therefore restricted to knife blade hoes, as these are the dominant tool.

Table 18. Interrow hoe properties table.

Mode of action	Cutting / severing, up rooting and some burial
Adjustments	Multiple. The height of the toolframe is adjusted via the depth wheel, which moves all weeding tools on that frame up and down by the same amount. Individual weeding tools are adjustable for vertical height and horizontal position. The toolbar should be at a height on the three point linkage such that the parallelograms are on average horizontal.
Crops	Any crop can be interrowed if it is planted in rows.
Crop size	From pre-emergence to typically a maximum of ~30 cm but some high clearance hoes can weed tall crops, e.g., maize, at over a meter.
Impact on crop	There should be no impact on the crop as it is bypassed by the weeding tools, but, incorrectly setup hoes can bury small crop plants and potentially large plants could have leaves damaged or ripped off.
Weed types	Both broadleafs and grasses, annuals and perennials, though, perennials less likely to be killed outright, more likely set back.
Weed size	Ideally cotyledon stage should be targeted, but, most weeding tools will kill weeds up to several true leaves, and, some even larger, and if not killed outright plants will be severely damaged.
Soil type	Depends on the weeding tool, but, most will work in any soil type
Soil tilth	As above, it varies with weeding tool, but, ideally a firm but friable tilth on the soil surface, very hard packed soils may need tillage points to break up the soil so horizontal knives can penetrate.
Stones	Varies with weeding tool, most will cope with a moderate level and size of stones, e.g., <5 cm, but, larger amounts and sizes of stones will negatively impact horizontal knives, and may cause some damage and increased wear. In such conditions cultivation type shares, e.g., duckfoot, will be required, and, when well setup will still achieve a high level of weed control
Soil moisture	For non-sticky soils knife blade hoes can work across a wide range of moistures, getting close to field capacity. For sticky soils knife blades loose their effectiveness when soil is to wet to flow over them. In all instances dry soils will result in greater weed death as they will desiccate before they can regrow.
Weather	Perfect weather is hot, dry and windy to maximise desiccation of weeds not killed outright by the hoe blades. Knife blade hoes will still function across most weather, except on sticky soils in the rain which will cause the knives to block.
Climate	Interrow hoes are used across a wide range of climates. The main limiting factor is very wet climates when weeding windows become too limited.
Plant residues	Again this varies with different weeding tools, but, sparse residues are mostly not a problem, but, larger pieces can collect on the weeding tool legs and cause blockages. Larger amounts of residues will mostly result in rapid blocking of the whole hoe.

Work rate	The largest hoes are 25 m wide and generally hoes are more aggressive as speed increases, with speeds of 15 kph or even more possible, so work rates can be substantial.

Further information.

- A key resource for hoe blades, particularly their design is "A review of knowledge: Inter-row hoeing and its associated agronomy in organic cereal and pulse crops" http://orgprints.org/6673/1/OF0312_2234_FRP.pdf [27].

Accuracy and intrarow / crop gap widths

Modern interrow hoes are highly effective at controlling weeds in the interrow, but, the weeds causing the most competition with the crop are the ones in the crop row / intrarow: called 'close to crop plant' weeds. Therefore making the intrarow width as small as possible means the maximum number of weeds are killed by the hoes. Table 19 gives the percentage of a paddocks surface that is weeded by an interrow hoe for a range of intrarow widths (crop gap) and interrow (crop row) spacings.

Table 19. The percentage of paddock surface that is interrow hoed, for a range of interrow (crop row) widths, for a range of intrarow (crop gap) spacings.

	Interrow spacing (cm)						
Intrarow Width	**10**	**15**	**20**	**25**	**30**	**35**	**40**
3 cm	70%	80%	85%	88%	90%	91%	93%
4 cm	60%	73%	80%	84%	87%	89%	90%
5 cm	50%	67%	75%	80%	83%	86%	88%
6 cm	40%	60%	70%	76%	80%	83%	85%
7 cm	30%	53%	65%	72%	77%	80%	83%
8 cm	20%	47%	60%	68%	73%	77%	80%

By minimising the intrarow width, fewer weeds have to be killed by alternative means. This is another major advantage of computer guided hoes: the increased level of accuracy means intrarow / crop gap widths can be much smaller than with manual steered systems.

A three centimetre crop gap is at the very limit of what is possible as it means there is only 15 mm from the center line and the hoe blade to its left and right; few crop plant are exactly on the center line, they also have width, and the hoe blades could be travelling at 15 kph. This limit is not only due to the limitations of GPS and vision guidance systems but also the steel of the hoe flexing. Four and five centimetre gaps are more practical for most situations.

A further accuracy issue for interrow hoeing is symmetry, in that the left and the right side of the drill, hoe and any other row following equipment have to be a perfect reflection of each other, because if not, then all row work has the follow the same direction of travel as the drill otherwise the non-symmetric rows will get hoed out. For the same reason, machinery needs to be mounted exactly on the center line of the tractor.

Setting up seed drills and hoes to achieve the above levels of accuracy is a challenge especially for wider machines, where using a tape measure can be highly frustrating and inaccurate. Experienced interrow hoe users use jigs to ensure the drill and hoe are accurately setup, at a quick glance. For the drill a simple wooden plank or beam with the row centers clearly marked on it is sufficient. The drill is lowered so the coulters / points are on or close to the ground and then the marks on the plank are visually lined up with the coulters, so any out of place point is easily visible. Ensuring there is no sideways play / wobble in the coulters is also critical for accuracy. For the hoes, jigs are used, consisting of lengths of wood the same width as the required intrarow width, and as long as the hoe is deep, for each crop row, joined at both ends by lengths of wood as long as the hoe is wide, making a kind of wide ladder shape. Separate jigs are therefore required for different intrarow sizes. Some operators have created jigs by setting pieces of steel into a concrete floor in the yard. While a considerable amount of work to create, they are highly accurate and robust.

The final piece in the accuracy jigsaw is hoe blade depth. The aim is to cut the weedlings through the hypocotyl / mesocotyle zone (section 3.4.3) which in most cases is in the top 1 cm of the soil. Hoe blades therefore need to run as shallow as possible, just deep enough so they don't exit the soil, but, no deeper. This will require adjustment of both depth wheel on the parallelogram unit and individual tools. Running blades any deeper will simply end up root pruning the weeds, which if conditions are moist, they will regrow, and the extra draft will increase stress on the hoe and fuel use.

Setting up an interrow hoe to do the best job possible therefore requires considerable expertise and attention to detail, even pedantry. Staff with more perfectionist tendencies are much more likely to achieve a good result than those with a 'she'll be right' attitude.

Intrarow weeding tools

Further to the importance of minimising the size of the intrarow / crop gap, to maximise weed kill, there are now a range of intrarow weeder tools, that are typically mounted on the toolframe of an interrow hoe. Most of these are designed for vegetables and are unsuited to arable crops, with the exception of mini-ridgers and finger weeders.

Mini-ridgers (Figure 30) create a precise ridge of soil in the crop row burying weeds but leaving the crop proud. Ridge height is determined by blade height, as excess soil flows over the top of the blade and only soil the height of the blade is moved sideways. For high speed use, narrower angles of the blades than the usual 90° are used.

Figure 30. Three 'mini-ridgers' small ridger (left) larger ridger (middle) large high speed ridger with narrower blade angle (right).

If weeds are covered by just 1 cm of soil, regardless of their size, they will be killed and if the crop is proud of the ridge by just 2 cm they will survive [13, 16]. As the weeds are entirely killed by burial, not uprooting and severing (section 6.5.1.1) weed death is not dependent on hot dry weather as it is for most other soil-engaging weeders. Mini-ridgers therefore offer the potential to achieve a high level of control of intrarow weeds with exceptionally simple and inexpensive technology.

Finger weeders consist of a circle of downward pointing, soil engaging, steel tines, sandwiched with a circle of flat typically softer tines - the fingers - that move soil among the plants (Figure 31).

Figure 31. Finger weeders. Left photo Machinefabriek Steketee BV.

Due to the soil engaging tines being shorter than the weeding fingers the fingers rotate faster than the speed of travel so stirring the soil and killing small weeds. Finger weeders are only suitable for larger crop plants sown at lower populations / intrarow spacing, e.g., maize, not cereal crops. Where they are suitable they are a great compliment to mini-ridgers as this allows a ridge to be built up and pulled down again controlling weeds with each operation.

Further information:

- The final frontier: Non-chemical, intrarow, weed control for annual crops with a focus on mini-ridgers bhu.org.nz/future-farming-centre/information/bulletin/2014-v4/the-final-frontier-non-chemical-intrarow-weed-control-for-annual-crops-with-a-focus-on-mini-ridgers [13].
- Mini-ridgers: Lethal burial depth for controlling intrarow weeds bhu.org.nz/future-farming-centre/information/bulletin/2018-v2/mini-ridgers-lethal-burial-depth-for-controlling-intrarow-weeds [16].

Other interrow hoes

There are a small range of other designs of interrow hoes. These include the basket weeder, which works by having two horizontal axels with wire cage 'baskets' on them, and a differential chain drive between them. The horizontal axis brush hoes, which has a cylindrical road sweeper type brush, but, with gaps for the crop to pass through. The vertical axis tine weeder consists of a number of small vertical axis rotors with typically three, angled, ridged, vertical tines on them about 30 cm long. All of these weeders have valuable attributes, some which make them unique and able to weed where nothing else can, but, they also have significant limitations which means they are considered less suitable for arable systems, especially at scale.

6.5.2. Using weeders and tools sequentially

Just like herbicides mechanical weeding tools can and should be used sequentially, i.e., different tools used in the same crop, just like using both a residual and foliar herbicide in the same crop. Clearly if the crop is not setup for interrow hoeing, then it can't be used. But, all the contiguous tools can be used in interrow ready crops. The quite different MoAs of the different tools mean that they can be highly complimentary. For example, a tine weeder could be used to implement a false seedbed, then used for a blind harrow post drilling but pre-emergence, then, following heavy rain, the spoon weeder can be used to break up the soil cap to free up the emerging crop plants, next, the more aggressive interrow hoe can keep the intrarow clean, alternating with the spring tine weeder which benefits from the looser tilth the interrow hoe creates and also weeds the intrarow. As the crop gets its first true leaves, mini-ridgers can be added to the interrow hoe, which again makes a great pairing with the spring tine weeder as that partly pulls down the mini-ridges, killing intrarow weeds both by the ridging up and pulling down. Later on the CombCut can be used to de-flower any remaining broadleaf weeds to prevent weed seed rain.

Using this multi-pronged approach, especially when paired with false seedbeds and good weed seedbank management, it is possible to achieve exceptional control of all therophyte weeds, and many perennials in any arable crop, all without any herbicides.

6.5.3. Band spraying

Band spraying is where the inter and intrarow areas are targeted with different herbicides. Typically in the interrow a broad-spectrum herbicide is used to kill everything, while, residuals and selectives are used in the intrarow. This is often used where the residuals and selectives are expensive so just treating the crop row significantly reduces the amount of herbicide used. Also if the herbicides MoA used in the crop row have a higher risk of resistance developing to them (Figure 12 page 34) then weeds in the interrow will not be exposed to them so reducing selection pressure. Another time band spraying is valuable where there are large amounts of residuals which prevent mechanical weeders (section 6.5.1) operating.

To use band spraying the crop needs to be in sufficiently wide rows, and drilled with sufficient accuracy that correctly following them is practical. If the farm is setup to use an incontiguous weeder such as an interrow hoe (section 6.5.1.6) and especially if they are using computer guidance systems these are excellent platforms from which to add band spraying, as this removing the stress of row-following from the tractor operator.

If a broad-spectrum herbicide is used in the interrow, it obviously needs to be kept off the crop. Figure 1 shows a band sprayer with hoods to prevent drift from the interrow to the intrarow.

Figure 32. Band sprayer.

As the aim is to kill everything in the interrow, drift from the crop row to the interrow is generally not an issue. However, the spray hoods also protect the spray from wind, so, the hoods can also allow for herbicide application in the crop row in windy conditions.

6.6. Rouging

Rouging is widely used in seed crops to control off types for certification, and, also noxious weeds in any crop, e.g., nightshade which is a contaminant of fresh vining peas. It will also have an increasing place in HR weed management (section 4.7.7) as part of monitoring for HR weeds in paddocks and taking action, for example, the removal of weeds that have survived spraying - regardless if it was poor application or suspected HR weeds.

6.7. Harvest and post harvest

The key focus of integrated weed management at harvest time is preventing weed seed rain (section 3.1). A good example of this is harvest weed seed control (HWSC). This is particularly important in Australia with its extensive cereal systems, and where a lot of research and farmer experimentation into killing weed seeds that pass through the header / combine has been undertaken.

6.7.1. Harvest weed seed control

Many arable weeds retain their seed at maturity and they are therefore harvested along with the crop grain or seed, passing through the header / combine and then sown back onto the paddock along with the chaff and straw. As a key focus of IWM is preventing weed seed rain (section 3.1) this is clearly problematic. A range of techniques have been developed in Australia over 20 plus years to minimise the return of weed seed passing through the header from joining the weed seedbank. Dramatic reductions of weed populations in subsequent crops have been achieved, e.g., an over 90% reduction in in-crop annual ryegrass emergence in just four years [26]. A key aspect of these approaches are the weed seeds end up in the chaff fraction. The techniques are:

- Narrow windrow burning;
- Chaff carts;
- Direct bailing;
- Seed mills;
- Chaff tramlining;
- Chaff lining.

Narrow windrow burning places both straw and chaff in a narrow band such that it burns sufficiently hot and for long enough to kill the seeds. Chaff carts collect the chaff in large tow-behind carts which dump the chaff in the paddock while moving. Piles are then burnt, sheep used to graze them, or they are just planted through the following season. Direct bailing passes both chaff and straw directly from the header to a bailer with the bales with weed seed in them being removed from the paddock. Seed mills very finely grind the chaff fraction, destroying the weed seeds. The main seed mill make is the Harrington Seed Destructor. Chaff tramlining places the chaff fraction in the header wheel tracks, either both or one only. It requires fully-matched, Controlled Traffic Farming (CTF) systems to be effective. It appears that by putting all the chaff and weed seed in one strip that a lot of the seed is dying, e.g., rotting, some germinates but fails to establish due to the chaff and harder wheelings, and for other unknown reasons, the bands are not producing large numbers of weeds. Likewise chaff lining places only the chaff fraction in a very narrow band down the centreline of the harvester which also appears to significantly increase weed seed mortality and other factors which stops the concentrated lines of weed seeds becoming problematic in following seasons.

There are a number of pros and cons of the techniques, including a huge variation in capital and running costs, the levels of nutrients removed from the paddock or lost through burning (mostly N), the inconvenience of pulling chaff carts or bailers behind the header, the ability to see harvest losses and adjust the header, labour requirements, fire risk and others. There are also yield limits for some systems, with 2 t/ha grain yield being the upper limit which is well below average yields in New Zealand. While HWSC has limited uptake to date in New Zealand there is considered to be significant value in the technique, especially for arable and seed crop dominated farms where the time and money invested would be spread over a larger hectarage.

FAR research has also shown stubble burning is an important method of non-chemical weed control, particularly for annual grass weed control, e.g. hairgrasses (*Vulpia* spp.) and bromes (*Bromus* spp.) in cereals and grass seed crops. Stubble burning has increased importance where growers use reduced cultivation systems or where weed seeds can germinate from depth. The key lesson from Australia is that the temperature of the burn needs to be sufficiently high for sufficiently long to achieve good weed kill, hence narrow windrow burning with its quite specific wind direction and speed requirements to achieve the optimum seed killing burn.

Further information:

- FAR Arable Extra, issue 105. 'Influence of stubble burning on weed control in cropping systems' www.far.org.nz/assets/files/blog/files/f71f0977-b1e4-4ddd-9b05-85017b37d535.pdf
- The Australian industry-led initiative 'WeedSmart' has a range of videos describing the HWSC concept and the individual approaches weedsmart.org.au/resources/hwsc/.

6.7.2. Natural predation

Particularly in arable systems, natural predation of seed at and post harvest can be substantial, with losses as high as 90% recorded [23]. Species predating seed include birds, rodents and especially invertebrates such as ground beetles. Birds and rodents are often pests in arable systems so encouraging them is undesirable, but, granivorous ground beetles are entirely beneficial and their populations can be boosted through techniques such as beetle banks[3] and cover crops (section 6.2). These techniques also promote predators (e.g., carabid beetles and spiders) of insect pests (e.g., aphids). Reducing broad spectrum insecticides that kill beneficial invertebrates, and using more selective / 'soft' chemistry, is therefore also important for promoting seed and insect pest predation. Further research is required into how weed seed predation can be optimised on New Zealand arable farms.

6.7.3. Stubble cultivations

Stubble cultivation immediately after harvest, if the soil is moist, can stimulate a range of crop seeds including cereals and oil seed rape as well as weed seeds, particularly grasses e.g., barren brome (*Bromus sterilis*) to germinate and then be killed. This is because these species lack primary dormancy so will readily germinate. If the same seeds is ploughed they will enter the dormancy cycle and if brought back up by further tillage will then germinate in subsequent crops over several years (section 3.1.4). Different forms of tillage mix weed seeds through the plough layer in different ways, see section 6.3.2.

6.7.4. Post harvest paddock weed assessment

As part of an integrated management approach, paddocks should be assessed / surveyed post harvest to look for signs of herbicide resistant weeds as described in section 4.7.7. If HR weeds are suspected then an immediate plan should be put in place to kill them. This need not be through herbicides, cultivation / tillage, and for some species, mowing can kill them. However, if they are producing seeds, it is best to manually remove either the whole plants, or at least, the parts of the plants with seeds and dispose of in a way that it is impossible for the seeds to find their way back to farmland, e.g., burning or landfill.

If there is a need to 'clean up' the paddock post harvest if glyphosate is being used consider the 'double knockdown' technique recommended to Australian arable farmers of a following the

[3] https://www.gwct.org.uk/farming/advice/sustainable-farming/beetle-banks/

glyphosate with a full strength paraquat or paraquat + diquat as a means of controlling weeds that survived the glyphosate see weedsmart.org.au/the-big-6/double-knock-preserve-glyphosate/.

6.7.5. Short term cover crop

If there is a gap of more than a few weeks post harvest and before the next cash crop consider sowing a quick growing cover crop to fill the gap, and also protect the soil from rain impacts and provide a top up of organic matter. Phacelia, buckwheat and mustard are all very quick growing, though if any area also grown as a seed crop they should be avoided. They can also be grown as a mixture, there is a growing body or research showing the benefits of mixtures (section 6.2).

6.8. Farm hygiene and managing seed dispersal

6.8.1. Cleaning farm equipment

As discussed in section 4.3.4 weed seeds rather than pollen are the most important mechanisms by which HR genes and plants are dispersed within and between farms. Weed scientists have previously expressed the importance of good hygiene to limit the spread of weeds between farms and this advice is even more important with herbicide resistant weeds. At the same time farmers have been reluctant to implement such practices due to the extra cost and especially time involved, particularly at busy times of year. However, the extra cost and inconvenience of having to manage HR weeds once present on a farm are also considerable, so the value of prevention is now much higher than previously. Good hygiene is also not a matter of absolute cleanliness: removing every last weed seed from every piece of equipment entering a farm would be very time consuming and difficult, but, like creating HR weeds, it is a numbers game, if the total number of weed seeds entering a farm is significantly reduced then the chances of a HR weed seed entering the farm is likewise significantly reduced. Also equipment can be rated for the risk of bringing on HR weed seeds: if it has just come from a property known to have HR weeds, then the risk is clearly high, so, extra effort should be extended to the clean down, compared with equipment from a low risk property, e.g., a pure stock farm.

Therefore having good weed seed hygiene systems and procedures needs to become as standard a practice as Health & Safety induction for contractors and other farm visitors.

The key is to have good systems: Create dedicated, easy to use, machinery clean down areas at the main entrances to the farm or farm yard, both wet clean for the likes of cultivation equipment, and dry clean for the likes of harvesters. Dry clean typically uses compressed air but also garden leaf blowers and vacuums can also be really effective. Ensure that all material removed from equipment is disposed of so that any seeds it contains can't make it onto the paddocks. Ideally equipment should be cleaned when leaving a property rather than arriving so HR material does not leave the source farm at all.

6.8.2. Animal feeds

It is clearly impossible to decontaminate fodder, such as hay, straw and silage for weed seeds as is done with equipment, so, it is essential to understand the likelihood of it containing HR weed seeds, which, is related to the HR weed status of the source farm. This highlights the importance of identifying which farms have HR weeds on them so informed decisions can be made.

Many weed seeds, especially broadleaf will pass through the digestive tract of livestock without being harmed - some even have increased germination rates due to removal of dormancy factors, e.g., fat hen (*Chenopodium album*). Therefore weed seeds that contaminate feeds such as grains, concentrates etc., are likely to pass through the stock and into the manure and thus act as a contamination route for HR weed seeds. Milling and most forms of processing are unlikely to kill more than a few weed seeds due to their small size, and especially for the broadleafs their hard seed coats. Extended heating, e.g., 90°C for several days or milling to the consistency of flour is required to kill weed seeds. Determining the source of the feed, its likelihood of being contaminated with HR weed seeds and the location where the manure will end up are key factors on estimating the risk of a given feed introducing HR weeds onto a farm.

Animals themselves may carry HR weed seeds in their guts when moved between farms. If the source property is known, or thought to have, HR weeds, consider standing off the stock until their last contaminated meal has cleared their digestive system.

6.8.3. Planting seed

The recent velvetleaf (*Abutilon theophrasti*) incursion via imported fodder beet seed highlights the difficulty of ensuring planting seed is completely free of contaminants, but, the same as for equipment clean down, it is a case of reducing risk not eliminating it completely. Always ask to see seed health certificates which includes tests for contaminant levels. For all seed lots, visually check for contaminant seeds, which for larger volumes of arable seeds, small weed seeds often settle out at the bottom of containers during transport allowing the presence of weed seeds to be more easily identified. If seed lots are contaminated consider having them re-cleaned. Clearly ordering seed in advance of planting dates is essential to allow for re-cleaning. Changing the purchasing of planting seed from just-in-time approaches to advance purchases to allow time for inspection of seed lots and then undertaking remedial action, is required.

7. Non-crop areas

There is often extensive use of herbicides to eliminate vegetation in non-crop areas such as fence lines, paddock margins, ditches, hedges, edges of driveways, etc. There are multiple reasons why a significant re-evaluation is required of this practice. The primary one is that it is a very high risk for the generation of HR weeds, particularly to glyphosate, due to it often being the only herbicide used and repeat application of the same MoA is the surest way to create HR weeds (section 4.7.6). As nearly all arable weeds, are species that have evolved to germinate in bare soil, using herbicides in non-crop areas, especially where there is good soil, e.g., fencelines, creates the perfect habitat for cropping weeds, which, is the opposite of what is desirable and the whole purpose of spraying, i.e., the practice is self-defeating. Further, a lot of the time the spraying is undertaken for no other reason than "it's what we always do" or for looks / aesthetics. However, following the logic that weed management is an economic activity (section 1.2) much non-crop area herbicide use is uneconomic, i.e., a waste of money. Finally, the use of herbicides in non-crop areas while common in New Zealand is not only uncommon in other countries, but in jurisdictions such as the European Union it is illegal.

With these multiple reasons to reduce to a minimum non-crop area use of herbicides what are the alternatives?

7.1. Fighting weeds with plants

As noted above, bare soil is the ideal environment for arable weeds, so, the clear solution is to eliminate the bare soil - with plants - i.e., fighting fire with fire / weeds with good plants. Using a biological solution also has multiple other positive benefits, e.g., resistance is very unlikely, the plants protect soil, and can enhance conservation biocontrol[4] if suitable flowering plants are included in the mixture, e.g., buckwheat, phacelia and particularly alyssum (*Lobularia maritima*) as this is a perennial. For ease of maintenance the plants should be perennial and highly competitive (Figure 33).

Figure 33. Suppressive prairie grass on headland. Photo Mike Parker.

[4] en.wikipedia.org/wiki/Biological_pest_control#Conservation

7.2. Migrating of weeds into crops

One of the reasons cited for spraying out paddock margins is that they are a source of weeds in the crop. However, where weed scientists have looked at weed ingress, both seeds and plants, from a range of paddock margins, they have found very little ingress, and that movement of weeds within paddocks is much greater than from paddock margins. Paddock margins are therefore mostly an insignificant source of weed seed unless they are regularly sprayed out to create a good environment for weeds, as discussed above.

7.3. When spraying is essential

Where it is a requirement to spray non-crop areas, e.g., part of seed certification, then, rotating MoAs and/or using tank mixes with different MoAs is absolutely essential. Using residual herbicides is also valuable as they are considered to be at lower risk of resistance developing, and, they give much longer control than glyphosate alone. As part of a FAR HR project, metsulfuron, simazine or terbuthylazine were identified as the most cost-effective. These mixtures provided excellent initial activity on weeds and provided some residual activity. The product TAG™G2 (a mixture of four herbicides, three of which belong to herbicide mode of action groups completely different from glyphosate) has shown good initial efficacy as well as residual activity and could be an acceptable alternative for rotating herbicides to avoid development of glyphosate resistance.

7.4. Other management options

If a fence is no longer needed consider removing it and cropping the land or plant it up in beneficial plants as discussed above.

Raise the bottom wire or do not electrify it so stock can eat out the bottom - they often graze these areas hard due to lack of dung and urine contamination.

Use a physical technique such as mowing or slashing along the fence. The perennial crop sectors (apples, grapes, etc.) have a wide range of mowers that can swing around obstacles, such as fence posts, and have low clearance, ideal for getting under bottom wires, that would allow a 'well kept' look to fence lines, without herbicides, and also be valuable in seed crops where certification rules require clean fence lines.

Further information:

FAR's 'Guidelines for minimising the development of glyphosate resistance along fence lines and field margins' www.far.org.nz/assets/files/editable//7964d990-822e-4fdd-acaa-be957252fa52.pdf

8. Herbicides in the wider environment

Overseas the presence of herbicides and other agrichemicals (insecticides / fungicides) in waterways and the wider environment is a well know issue and legislation has been enacted to address it. While the current proposals to update the New Zealand National Policy Statement for Freshwater Management, only addresses sediment, nitrogen (nitrates) and bacteria it is likely that future revisions will include agrichemicals and other chemical contaminants. It is therefore in farmers' best interest that the agricultural sector is proactive in addressing potential sources of water contamination, so it is less likely that prescriptive controls that limit rates, timing, and even product withdrawal, are implemented.

Herbicides can enter waterways in a wide range of ways:

- Stores hold concentrated chemicals; a fire or leak can have a huge impact downstream;
- Drips or spills of concentrated chemical at sprayer filling can wash off concrete or hardcore into drains and watercourses;
- Over-spraying watercourses is careless and jeopardises aquatic life and water quality;
- Drift concerns neighbours and can harm aquatic life and water quality;
- Drain flow is the main way herbicides leave the paddock in the winter months. Herbicides attached to soil particles or in drainage water enter watercourses when drains are flowing;
- Surface run-off carrying soil and pesticides can occur on most soils and slopes after heavy rain and can be channelled by tramlines;
- Cleaning sprayers produces large quantities of dilute pesticide that can easily reach drains if poorly managed;
- Disposing of pesticide containers by burial is illegal and can cause long-term damage to water quality.

Key points for minimising risks:

- Establish grass buffer strips at least 6m wide, or tree planted riparian strips, beside watercourses, or use a 5m no-spray zone;
- Do not spray when heavy rain is forecast within 48 hours of application; nor when soil is very wet or drains are running or are likely to run;
- Only spray in suitable, settled weather, preferably when soil is moist;
- Take care when filling or emptying the sprayer to avoid spills;
- Wash sprayer in the paddock and park under cover;
- Pressure- or triple-wash and drain pesticide containers before storing them under cover and use an approved disposal contractor.

9. References

1. Bliss, K., Plant teams in the field - Intercropping in practice in the UK and Sweden. Organic Research Centre Bulletin, 2019. 129(Autume): p. 8-9. http://www.organicresearchcentre.com/?go=Information%20and%20publications&page=ORC%20Bulletin
2. Caldwell, B. and Mohler, C.L., Stale seedbed practices for vegetable production. HortScience, 2001. 36(4): p. 703. https://journals.ashs.org/hortsci/view/journals/hortsci/36/4/article-p703.xml DOI:10.21273/hortsci.36.4.703
3. Cook, S.K., Clarke, J., Moss, S., Butler-Elis, C., Stobart, R., Davies, K., Gosling, P., and Storkey, J., Managing weeds in arable rotations – a guide. 2017. https://ahdb.org.uk/knowledge-library/managing-weeds-in-arable-rotations-a-guide
4. Dias, L.S., Allelopathic activity of decomposing straw of wheat and oat and associated soil on some crop species. Soil and Tillage Research, 1991. 21(1): p. 113-120. http://www.sciencedirect.com/science/article/pii/016719879190009M DOI:10.1016/0167-1987(91)90009-M
5. Diggle, A.J., Neve, P.B., and Smith, F.P., Herbicides used in combination can reduce the probability of herbicide resistance in finite weed populations. Weed Research, 2003. 43(5): p. 371-382. https://onlinelibrary.wiley.com/doi/abs/10.1046/j.1365-3180.2003.00355.x DOI:10.1046/j.1365-3180.2003.00355.x
6. Gallandt, E.R., Halloran, J., Kersbergen, R., Mallory, E., and Sideman, E., Managing weed seed rain: A new paradigm for organic and low-input farmers. 2010, Sustainable Agriculture Research & Education (SARE): Washington, Maryland, USA. https://projects.sare.org/project-reports/lne06-237/
7. James, T. and Rahman, A. Can we successfully manage weeds by manipulating the weed seed bank? in 24th Asian-Pacific Weed Science Society Conference. 2013. Bandung, Indonesia: Asian-Pacific Weed Science Society in collaboration with Weed Science Society Of Indonesia. https://apwss.org/documents/24th%20APWSS%20ConferenceProceeding.pdf
8. Jasieniuk, M., Anita, L.B.-B., and Ian, N.M., The evolution and genetics of herbicide resistance in weeds. Weed Science, 1996. 44(1): p. 176-193. www.jstor.org/stable/4045802
9. Jordan, V.W.L. and Hutchinson, J.A., Multifunctional crop rotations: the contributions and interactions for integrated crop production and nutrient management in sustainable cropping systems. Aspects of Applied Biology, 1996. 47(Rotations and cropping systems): p. 301-308
10. Leighty, C.E., Crop Rotation, in Soils & Men: Yearbook of Agriculture 1938, Anon., Editor. 1938, United States Department of Agriculture: Washington. https://naldc.nal.usda.gov/download/IND50000140/PDF
11. Lemerle, D., Verbeek, B., and Coombes, N., Losses in grain yield of winter crops from *Lolium rigidum* competition depend on crop species, cultivar and season. Weed Research, 1995. 35(6): p. 503-509. https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1365-3180.1995.tb01648.x DOI:10.1111/j.1365-3180.1995.tb01648.x
12. Liebman, M. and Gallandt, E.R., Many little hammers: ecological management of crop-weed interactions, in Ecology in Agriculture, Jackson, L.E., Editor. 1997, Academic Press: San Diego, CA. ISBN 978-0123782601
13. Merfield, C.N., The final frontier: Non-chemical, intrarow, weed control for annual crops with a focus on mini-ridgers. The FFC Bulletin, 2014. 2014-V4 http://www.bhu.org.nz/future-farming-centre/information/bulletin/2014-v4/the-final-frontier-non-chemical-intrarow-weed-control-for-annual-crops-with-a-focus-on-mini-ridgers
14. Merfield, C.N., False and Stale Seedbeds: The most effective non-chemical weed management tools for cropping and pasture establishment. The FFC Bulletin, 2015. 2015(V4): p. 25. http://www.bhu.org.nz/future-farming-centre/information/bulletin/2015-v4/false-and-stale-

seedbeds-the-most-effective-non-chemical-weed-management-tools-for-cropping-and-pasture-establishment
15. Merfield, C.N., Understanding biostimulants, biofertilisers and on-farm trials. The FFC Bulletin, 2016. 2016(V1). http://www.bhu.org.nz/future-farming-centre/information/bulletin/2016-v1/understanding-biostimulants-and-biofertilisers
16. Merfield, C.N., Mini-ridgers: Lethal burial depth for controlling intrarow weeds. The Future Farming Centre Bulletin, 2018. 2018(V2). http://www.bhu.org.nz/future-farming-centre/information/bulletin/2018-v2/mini-ridgers-lethal-burial-depth-for-controlling-intrarow-weeds
17. Merfield, C.N., Rotations and their impact on soil health. 2019, The BHU Future Farming Centre: Lincoln. http://www.bhu.org.nz/future-farming-centre/ffc/information/soil-management/the-fundamentals-of-soil-nutrient-management,-soil-testing-and-fertiliser-recommendations-2015-ffc-merfield.pdf
18. Moss, S.R., Herbicide-resistance in weeds, in Weed Research: Expanding Horizons, Hatcher, P.E. and Froud-Williams, R.J., Editors. 2017, John Wiley & Sons: Chichester, UK. ISBN 9781119969143. https://onlinelibrary.wiley.com/doi/book/10.1002/9781119380702
19. Powles, S.B. and Preston, C., Herbicide cross resistance and multiple resistance in plants. 2016, Herbicide Resistance Action Committee. https://hracglobal.com/files/Herbicide-Cross-Resistance-and-Multiple-Resistance-in-Plants.pdf
20. Rahman, A., James, T.K., Bourdôt, G., and Grbavac, N., Weed seedbank estimation, spatial distribution, decline and potential for predicting future weed populations. Plant Protection Quarterly, 1998. 13: p. 117–122. http://www.weedinfo.com.au/ppq_abs13/ppq_13-3-117.html
21. Roberts, H.A., ed. Weed Control Handbook. 7th ed. 1982, Blackwell Scientific Publications: Oxford. ISBN 0632010185
22. Roberts, H.A. and Feast, P.M., Fate of seeds of some annual weeds in different depths of cultivated and undisturbed soil. Weed Research, 1972. 12(4): p. 316-324. https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1365-3180.1972.tb01226.x DOI:10.1111/j.1365-3180.1972.tb01226.x
23. Sarabi, V., Factors that influence the level of weed seed predation: A review. Weed Biology and Management, 2019. 19(3): p. 61-74. https://onlinelibrary.wiley.com/doi/abs/10.1111/wbm.12186 DOI:10.1111/wbm.12186
24. Storrie, A.M., ed. Integrated weed management in Australian cropping systems. 2014, Grains Research and Development Corporation. ISBN 978-1-921779-61-9. https://grdc.com.au/resources-and-publications/all-publications/publications/2014/07/iwmm
25. Thompson, A.R. The future of weed research in the UK – a chemical industry viewpoint in The Future of Weed Research in the UK. 2008. London: HGCA
26. Walsh, M., Newman, P., and Powles, S., Targeting weed seeds in-crop: A new weed control paradigm for global agriculture. Weed Technology, 2013. 27(3): p. 431-436. https://www.cambridge.org/core/journals/weed-technology/article/targeting-weed-seeds-incrop-a-new-weed-control-paradigm-for-global-agriculture/BADC62B6430FDA1546041DB8A59D4492 DOI:10.1614/WT-D-12-00181.1
27. Welsh, J.P., Tillett, N., Home, M., and King, J.Q., A review of knowledge: Inter-row hoeing and its associated agronomy in organic cereal and pulse crops. 2002, EFRC, SRI and ADAS. http://orgprints.org/6673/1/OF0312_2234_FRP.pdf