Foundation for Arable Research
PO Box 23133
Templeton, Christchurch 8441
New Zealand

Phone: +64 3 345 5783
Email: far@far.org.nz
Web: www.far.org.nz

FAR Focus
ISSN 2357-1691 (PDF)

FAR Focus 17: Maize weed management
ISBN 978-0-9941286-9-0 (PDF)
ISBN 978-1-0670713-0-1 (Print)

ADDING VALUE TO THE BUSINESS OF CROPPING

FAR FOCUS

Foundation For Arable Research

Issue 17, March 2025

Maize weed management

ISSUE 17

- Herbicide resistance
- Problem weeds
- Herbicide options
- On-farm biosecurity

ADDING VALUE TO THE BUSINESS OF CROPPING

FAR Focus 17
Maize weed management

Contents

This FAR Focus is intended to provide accurate and adequate information relating to the subject matters contained in it. It has been prepared and made available to all persons and entities strictly on the basis that FAR, its researchers and authors are fully excluded from any liability for damages arising out of any reliance in part or in full upon any of the information for any purpose. No endorsement of named products is intended nor is any criticism of other alternative, but unnamed product.

1. Introduction and background

Key points:

- Weeds are a key production issue in maize and unmanaged weeds can significantly reduce maize yields and profit.
- Herbicide resistance is becoming more common and making weed management more difficult.
- A 2021-22 survey of maize crops found up to 61% of farms had fathen resistant to atrazine Group 5, and/or summer grass resistant to nicosulfuron (Group 2).
- More widely, further surveys have found up to 71% of arable farms have herbicide resistance, principally to Groups 1 and 2.
- Some weeds that are a biosecurity concern also have herbicide resistance in their countries of origin, making on-farm vigilance, rapid identification and containment essential.

This second edition FAR Focus on maize weed management draws on information from over 15 years of investment into maize weed research. It covers the principles of weed management and provides guidance for the successful management of both broadleaf and grass weeds in maize.

Weeds are currently estimated to cause losses of up to 35% of global crop production in some crops. A recent FAR 2021 cropping sequence survey identified weed management as the 'Number 1' agronomic challenge for arable growers in New Zealand.

The current agricultural system manages to keep weed pressure within 10% of yield loss, but there is an overreliance on chemicals for weed management in cropping systems. Agricultural chemical crop protection sales in New Zealand are estimated at $350 million annually with herbicides accounting for 45% or ca. $158 million .

In New Zealand, fewer and fewer herbicides are available due to regulation, registration and export market demands. A gradual failure in field management of key weeds is also being observed on-farm. An increasing likelihood of importing new herbicide resistant weeds exists, which are already impacting production in the ~$250M seed multiplication export industry.

This breakdown in effective management of weeds in cropping systems threatens the profitability of cropping businesses and the rural communities they are a part of. Herbicide resistance, biosecurity and the cost of weeds are thus key issues underpinning weed management.

1.1 The cost of weeds

Yield losses ranging from 15% to 56% for silage and 15% to 61% for grain have been observed in New Zealand maize systems. These losses, combined with herbicide costs, can be used to calculate illustrative gross margins for silage and grain production, with and without herbicide-based weed management (Tables 1 and 2). It is important to note that these gross margins are indicative, as production costs and the market prices of maize silage and grain are subject to fluctuation.

Table 1. Illustrative gross margin for maize silage with and without herbicide-based weed management with a resulting crop loss between 15% to 56%.

	Weeded maize silage crop	Un-weeded maize silage crop (excluding herbicides)	
	No crop loss associated with weeds	15% crop loss	56% crop loss
Yield (t/ha)	22	18.7	9.68
Crop value ($/t)	$270	$270	$270
Income ($/ha)	$5,940	$5,049	$2,614
Field costs ($/ha)	$2,600	$2,200	$2,200
Gross margin ($/ha)	$3,340	$2,849	$414

Note. These are illustrative gross margins as production costs and particularly the price of maize silage and grain fluctuate.

Table 2. Illustrative gross margin for maize grain with and without herbicide-based weed management with a resulting crop loss between 15% to 61%.

	Weeded maize grain crop	Un-weeded maize grain crop (excluding herbicides)	
	No crop loss associated with weeds	15% crop loss	61% crop loss
Yield (t/ha)	13.0 wet 10.5 dry	11.1 wet 9.0 dry	4.3 wet 3.5 dry
Crop value ($/t dry)	$500	$500	$500
Income ($/ha)	$5,265	$4,475	$1,745
Field costs ($/ha)	$2,600	$2,200*	$2,200
Cartage cost ($50/t/50 km wet)	$650	$553	$215
Drying cost ($46/t wet)	$598	$508	$198
Total cost ($/ha)	$3,848	$3,261	$2,614
Gross margin ($/ha)	**$1,417**	**$1,214**	**-$868**

Note. These are illustrative gross margins as production costs and particularly the price of maize silage and grain fluctuate.

1.2 Herbicide resistance

An increasing frequency of resistant weeds to current and new herbicides has been detected in recent MBIE-funded research. Across all maize growing regions up to 71% of farms surveyed had at least one weed resistant to either Group 1 or 2 herbicides.

A 2021-22 survey of maize crops in the major maize growing areas in the North Island found resistance on 61% of farms in the Waikato, 31% in Bay of Plenty and 9% in Hawke's Bay. Resistant weeds found were fathen (*Chenopodium album*) resistant to atrazine (Group 5), and summer grass (*Digitaria sanguinalis*) resistant to nicosulfuron (Group 2).

More generally, surveys of all arable farm types have found a wide range of resistant weeds. These include wild oats (*Avena fatua*), annual and perennially ryegrasses (*Lolium hybridum*, *multiflorum* and *perenne*), canary grass (*Phalaris minor*), sow thistle (*Sonchus asper* and *oleraceus*), prairie grass (*Bromus catharticus*), poa species, chickweed (*Stellaria media*), willow weeds, (*Persicaria lapathifolia* and *maculosa*) rayless chamomile (*Matricaria discoidea*) resistant to Groups 1 and/or 2, e.g., fenoxaprop, haloxyfop, pinoxaden, pyroxsulam, clodinafop, chlorsulfuron, iodosulfuron, and clethodim.

Herbicide resistance is therefore widespread in both geography and weed species. Relying only on herbicides for weed management is only going to increase herbicide resistance, hence the need to move to Integrated Weed Management (IWM).

Herbicide resistance and how to manage it is specifically addressed in Section 3 and the whole integrated weed management approach (Section 2) aims to minimise the risk of resistance and provide best management where it does occur.

1.3 Biosecurity

Nearly all of New Zealand's arable weeds, including the most problematic ones, have been introduced accidentally or deliberately from places such as Europe and others are still awaiting the opportunity. Weeds like black-grass (*Alopecurus myosuroides*) would be very costly in terms of management, reduced yields and lost markets, were they to become established.

Current border security procedures reduce the likelihood of new weed species incursions into New Zealand but increasing international trade and travel provide an on-going risk of new weeds entering the country and establishing on farms. Imported seed, second-hand farm machinery and international containers are a particularly high risk. Non-naturalised weeds, once established, are often very difficult and expensive to eradicate, as recent black-grass and velvetleaf (*Abutilon theophrasti*) incursions have demonstrated.

In addition to harmful weed species not present in New Zealand, there is an increasing risk of importing herbicide resistance via seed imports. Research in 2021 and 2022, under the Better Border Biosecurity research collaboration (www.b3nz.org.nz) funded from AgResearch's Strategic Science Investment Fund, found that 80% of 56 commercial ryegrass seed lots tested had Group 1 and/or 2 resistance. Levels of resistance were similar for seed imported from the USA and EU as NZ originating seed lots, and there was no difference among the seed companies. It was noted that if sufficient seed were tested that resistance would likely be found in all seed lots.

In addition, non-naturalised weeds, such as black-grass, have high rates of herbicide resistance in other countries, so introduced seed could be both unwanted and herbicide resistant making eradication and management even harder.

It is therefore vital for growers to effectively monitor their crops for both non-naturalised and herbicide resistant weeds. Any finds should be reported to the Ministry for Primary Industries (MPI), FAR, herbicide companies, and/or regional council staff as appropriate, so that the potential non-naturalised weed and/or herbicide resistance can be identified and the risk associated with its presence can be assessed, and appropriate action taken as quickly as possible.

Biosecurity therefore exists at both the national level - our land and sea borders - and the farm level. Farm level biosecurity means actively preventing, or at least minimising, the ingress of weeds onto the farm, through actions such as machinery clean down, using quality tested seed, having a quarantine area for livestock brought onto the farm to clean out, and actively managing bought in livestock feed and bedding (e.g., straw, hay and grain) on the assumption it contains unwanted weed seed.

More information on biosecurity, including detailed information on weed species of particular concern are covered in Section 4.

1.4 Conclusions

Weed management is moving from the era where herbicides were simple, inexpensive and reliable tools, to one of herbicide resistant weeds, ongoing border breaches by non-naturalised weeds and more complex weed management. Internationally, weed experts agree that integrated weed management (IWM), which uses a range of approaches, synergistically, is the only way to maintain effective weed management in the face of these challenges.

2. The integrated weed management (IWM) framework

Key points:

- The international weed science community is clear that integrated weed management (IWM) is the future of weed management.
- The European Union project IWMPRAISE has developed an IWM framework with five management 'pillars' and three intervention times in a weed's life cycle.
- The five pillars are:
  i. Monitoring and evaluation,
  ii. Diverse cropping systems,
  iii. Field / soil management,
  iv. Cultivar choice and establishment,
  v. Direct control.
- The three intervention steps in a weed's life cycle are:
  i. Preventing establishment,
  ii. Reducing crop impacts,
  iii. Minimising seed return.
- Whatever the intervention, targeting weeds when they are small is generally more effective.

With the multiple challenges facing herbicides, integrated weed management (IWM) is viewed by the global weed science community as the best way forward for weed management. IWM is based on integrating a diverse range of weed management tools and techniques including herbicides, physical approaches such as mechanical weeding, and cultural methods such as rotations, across all stages of the weed life cycle and crop production.

2.1 Targeting the three key stages of weed life cycles

A recent paper from the large European IWMPRAISE project provides an overarching framework for IWM. First it highlights that weed management needs to occur over the whole life of the weeds (and crop) with the aim of reducing their current and future populations. This is through targeting the three key stages of weed life cycles:

1. Prevention of weed establishment from seeds, rhizomes or tubers,
2. Reduction of the adverse impact of emerged weeds on the crop,
3. Reduce seed rain and the replenishment of the weed seed or vegetative bud bank (Figure 1).

2.2 The five pillars of integrated weed management

For each of the three weed life stages there are multiple tactics that need to be integrated to achieve good weed management. These tactics are split into five 'pillars':

1. Monitoring and evaluation,
2. Diverse cropping system,
3. Field / soil management,
4. Cultivar choice and establishment,
5. Direct control.

Figure 2 shows the IWMPRAISE five pillars diagram.

2.2.1 Monitoring and evaluation

Monitoring and evaluation are at the heart of IWM. Monitoring involves regularly scouting paddocks, especially around establishment, to determine what weed species are present (and their population sizes) and therefore the best weed management tactics. Evaluation checks the efficacy of your management tactics, particularly if there are weeds that have escaped herbicide treatments and may therefore be resistant (requiring additional / alternative treatments for control). Monitoring needs to continue through to, and after, harvest to identify whether post-harvest weed seed management is required, and whether potentially herbicide resistant weeds require ongoing control.

This is also where precision / digital agriculture techniques, such as weed mapping and sensing are likely to play an increasingly important future role.

2.2.2 Diverse cropping systems

Cropping system diversification includes using a greater range of herbicides, especially those from groups with lower or no resistance, a more diverse rotation with annual crops from a larger spectrum of plant families, and, ideally, a pasture phase. More diverse rotations also facilitate the use of a wider range of herbicide groups. Alternating between spring and autumn sown crops is a valuable diversification option. Cover crops, including intercrops, are another means of diversifying cropping systems. Intercrops are where two or more species of plants are grown together. For example, growing wheat and faba bean as a cash crop mixture, or undersowing maize with clover as a cash and cover crop mix.

Figure 1. The stages of a weed's life cycle when different management tactics will have the greatest effect.

Figure 2. Framework for the planning and design of holistic IWM strategies that require combinations of individual management tools appropriately selected from each of the five pillars of IWM: Diverse cropping systems, cultivar choice and establishment, field and soil management, direct control and the cross-cutting pillar monitoring and evaluation 2.

2.2.3 Field/soil management

Good soil management starts with ensuring macro and micro nutrients and pH are at optimum so crops are healthy and more competitive. Physical soil conditions are just as important, so minimising compaction, creating a good seedbed in tillage systems, or using reduced tillage systems such as min-till and direct-drilling / no-till are all important. Putting nutrients down the drill spout rather than broadcasting will ensure the crop accesses them before the weeds.

2.2.4 Cultivar choice and establishment

Cultivar (or hybrid) choice and establishment techniques can set up strong vigorous crops that are quick to emerge and achieve canopy closure to suppress weeds. Optimum sowing dates and depths along with high quality seed are the foundation; increased sowing rates, more competitive cultivars and sowing patterns such as narrower rows build on this foundation.

2.2.5 Direct control

Direct control includes traditional herbicide based weed management and is supported by an ever increasing range of mechanical weeding options. Mechanical weeding is now a mature technology with mainstream agricultural machinery manufacturers selling a wide range of weeding equipment including integrated computer guidance systems. Minimising weed seed shed - the weed seed rain - is vital, particularly from herbicide resistant weeds.

2.3 Many little hammers - or all the tools in all the toolboxes

IWM is often likened to using 'many little hammers'. Many smaller individual weed management tactics and tools are integrated to create an effective and resilient weed management system, compared with just relying on herbicides. This is a similar metaphor to 'all the tools in all the toolboxes' i.e., don't just rely on the chemical (herbicide) tool box, but use as many tools as possible from the mechanical and cultural toolboxes. While more complex than chemical weed management, IWM provides more points in the crop's production cycle to tackle weeds, so if one tactic does not work as well as planned, other tactics can pick up the slack.

2.4 IWM conclusions

IWM uses herbicides as part of a more diverse approach to managing weeds. This can seem daunting, but using herbicides as part of a diversified weed management minimises the risk of resistance emerging on your farm and ensures stewardship of increasingly limited herbicide chemistry. IWM also addresses market access issues, with markets such as the European Union placing increasing restrictions on, or even prohibiting, existing chemistry and expecting countries supplying them to do the same.

This FAR Focus uses the IWMPRAISE three weed life stages (Figure 1) as the main structure of this report and the five pillars within each of the life stage sections. That is within the context of herbicide resistance and biosecurity.

3. Herbicide resistance

Key points:

- Managing herbicide resistance is the responsibility of all arable growers.
- Herbicide resistance is widespread on New Zealand arable farms including maize crops, primarily to Group 1 (fops and dims) and Group 2 (sulfonylureas), though resistance to Group 4 (dicamba and 2,4-D), Group 5 (atrazine), Group 9 (glyphosate) and Group 22 (paraquat) also exist.
- A considerable number of weed species present in New Zealand are resistant to herbicides overseas, so are at heightened risk of developing resistance here.
- All growers need to develop resistance management plans, not just for maize, but for the whole farm, based on an integrated weed management approach.
- Non-crop areas, such as fence-lines, are potential sources of herbicide resistant weeds if not correctly managed.

In New Zealand, herbicide resistance, coupled with limited new herbicide chemistry / new groups, and challenging product registration, are the biggest threats to ongoing herbicide based weed management. Keeping existing herbicides working is primarily the job of growers, with advice and support from industry. Knowledge is power, so this section details current information on existing and potential herbicide resistance and how to best manage herbicides to minimise risk.

3.1 Herbicide resistance is widespread in maize and other arable crops

Herbicide resistance is a major concern for growers all over the world. The first weed to evolve herbicide resistance in New Zealand was fathen (*Chenopodium album*) to atrazine (1979 in Waikato maize). In 1980, redshank / willow weed (*Persicaria maculosa*) was also found to be resistant to atrazine in Waikato, and in 2005 fathen resistant to dicamba in Waikato and summer grass (*Digitaria sanguinalis*) resistant to nicosulfuron were identified in Bay of Plenty and Waikato. All of these incidences were in maize and all were identified by growers, advisors etc in an ad-hoc manner, e.g. due to weeds not being killed by a herbicide application.

Since 2019 a number of systematic weed surveys have been carried out specifically looking for herbicide resistant weeds. As highlighted in the introduction, in 2021 and 2022 random surveys of maize crops in the Waikato, Bay of Plenty and Hawke's Bay, found significant numbers of farms with resistant fathen and summer grass (Table 3).

Across all the surveys, of a range of crops, on arable farms from across NZ the number of farms with resistance ranged from 11% to 71% (Figure 3).

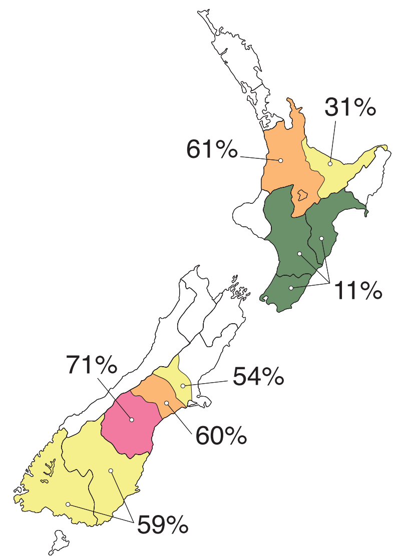

Figure 3. Map of the percentage of farms where at least one herbicide-resistant weed was found during random surveys between 2019 and 2023. Numbers in brackets indicate data from a separate 2021-22 AgResearch survey of maize crops. Grey areas were not surveyed. FAR Arable Extra X137 Five years of herbicide resistant weed surveys on arable farms.

Table 3. Herbicide resistant weed species identified from random surveys conducted in New Zealand maize crops in 2021 and 2022. Species listed are those that tested positive for herbicide resistance, along with the chemical(s) to which they were resistant. Also shown is the number of farms where each species of resistant weed was found. Source, FAR Arable Extra, Issue 137, Five years of herbicide resistant weed surveys on arable farms.

Location	Farms with resistance	Resistant weed	Species	Herbicide	Group	No. of farms with resistance
Waikato	22 out of 36 (61%)	Fathen	*Chenopodium album*	atrazine	5	18
		Summer grass	*Digitaria sanguinalis*	nicosulfuron	2	7
Bay of Plenty	5 out of 16 (31%)	Fathen	*Chenopodium album*	atrazine	5	4
		Summer grass	*Digitaria sanguinalis*	nicosulfuron	2	1
Hawke's Bay	1 out of 11 (9%)	Summer grass	*Digitaria sanguinalis*	nicosulfuron	2	1

Based on these surveys, it is clear that herbicide resistance is widespread geographically and a wide range of weed species are resistant (see herbicide resistance section in the introduction). The survey identified 12 new herbicide resistant species. Additionally, a large amount of herbicide resistance research indicates that unless further action is taken, more resistance is highly likely. For example, weeds that are common in New Zealand maize crops that are not currently resistant in New Zealand but are resistant in other countries, are considered the highest risk (Table 4).

Table 4. Weed species of particular relevance to maize, that have resistance to specific herbicide groups (mode of action) overseas but not yet in New Zealand, which increases the risk of them developing resistant to those herbicide groups in New Zealand without improved resistance management. Source weedscience.org and Dr Trevor James, AgResearch Ltd., pers. comm.

Common name	Species	Countries	Resistant to
Velvetleaf	*Abutilon theophrasti*	USA	Group 5, atrazine
Purple amaranth	*Amaranthus lividus*	France	Group 5, atrazine
Redshank / willow weed	*Persicaria maculosa*	Spain	Group 5, atrazine
Slim amaranth	*Amaranthus hybridus*	8 countries	Group 2, sulfonylureas, Group 5, atrazine, Group 9, glyphosate
Redroot	*Amaranthus species*	Canada, France Switzerland	Group 2, sulfonylureas, Group 5, atrazine
Redroot	*Amaranthus species*	10 countries	Group 2, sulfonylureas, Group 5, atrazine
Fathen	*Chenopodium album*	14 countries	Group 5, atrazine
Fathen	*Chenopodium album*	New Zealand	Group 4, dicamba
Fathen	*Chenopodium album*	Ukraine	Group 2, sulfonylureas
Cobbler's pegs	*Bidens Pilosa*	Brazil	Group 2, sulfonylureas, Group 5, atrazine
Swamp beggar's ticks	*Bidens tripartite*	Austria	Group 5, atrazine
Plumeless thistle	*Carduus acanthoides*	Argentina	Group 4, 2,4-D, Group 9, glyphosate
Wavy-leaved fleabane	*Conyza bonariensis*	USA, Switzerland	Group 9, glyphosate, Group 22, paraquat
Canadian fleabane	*Conyza canadensis*	6 countries	Group 2, sulfonylureas, Group 5, atrazine, Group 9, glyphosate
Broad-leaved fleabane	*Conyza sumatrensis*	Brazil	Group 2, sulfonylureas, Group 9, glyphosate
Thornapple	*Datura stramonium*	USA	Group 5, atrazine
Summer grass	*Digitaria sanguinalis*	China, France, NZ	Group 2, sulfonylureas
Barnyard grass	*Echinochloa crus-galli*	9 countries	Group 2, sulfonylureas, Group 5, atrazine
Crowfoot grass	*Eleusine indica*	4 countries	Group 9, glyphosate, Group 22, paraquat
Italian ryegrass	*Lolium multiflorum*	USA, Brazil	Group 1, fops and dims, Group 2, sulfonylureas , Group 9, glyphosate
Witchgrass	*Panicum capillare*	Canada	Group 5, atrazine
Smooth witchgrass	*Panicum dichotomiflorum*	Spain	Group 5, atrazine
Broomcorn millet	*Panicum miliaceum*	China	Group 2, sulfonylureas
Wireweed	*Polygonum aviculare*	Netherlands	Group 5, atrazine
Cornbind	*Fallopia convolvulus*	Austria, Germany	Group 5, atrazine
Pale willow weed	*Persicaria lapathifolia*	France, Germany, Spain	Group 5, atrazine
Groundsel	*Sencio vulgaris*	Canada, Belgium, USA	Group 5, atrazine
Yellow bristle grass	*Setariaa pumila*	Canada, France, USA, Spain	Group 5, atrazine
Rough bristle grass	*Saetaria verticillata*	Spain	Group 5, atrazine
Green bristle grass	*Setaria viridis*	France, Spain, USA, Canada	Group 2, sulfonylureas, Group 5, atrazine
Black nightshade	*Solanum nigrum*	8 countries (including NZ)	Group 5, atrazine
Sow thistle / Puha	*Sonchus oleraceus*	France	Group 5, atrazine
Chickweed	*Stellaria media*	Germany	Group 5, atrazine
Noogoora bur	*Xanthium occidentale*	USA	Group 2, sulfonylureas

Weeds of particular concern of developing resistance in New Zealand to specific herbicide groups are:

- *Amaranthus* spp. gaining resistance to atrazine (Group 5), sulfonylureas (Group 2) and glyphosate (Group 9).
- Fathen already has dicamba (Group 4) resistance. Overseas plants have become resistant to Group 2 within 4 to 6 years.
- Fleabanes are generally not a weed of maize but they are common on roadsides, and could easily evolve resistance to glyphosate (Group 9) there. Wind-borne seed could then cause problems in maize paddocks.
- Thornapple. Some growers are having problems due to its late germination.
- Black nightshade is already resistant to cyanazine (Group 5) in New Zealand. It is likely to evolve resistance to atrazine (Group 5) in maize if it is not rotated.
- Grass weeds: summer grass, witchgrass, smooth witchgrass, broomcorn millet, barnyard grass and crowfoot grass. Sulfonylurea (Group 2) resistance is the greatest threat. They are difficult to manage due to late emergence. Pre-emergence generally highly effective, and there is a variety of post-emergence options. Ensure you use the full range of post-em options available.
- For annual ryegrass, the largest threat is glyphosate (Group 9) resistance from vineyards where it is a major problem, and potentially from roadsides. Farm biosecurity remains very important for its management.
- Bristle grasses - yellow, rough and green - are at risk of resistance to nicosulfuron (Group 2). They are also a wider problem than maize as they reduce pasture quality and utilisation.
- Purple nutsedge (*Cyperus rotundus*) is difficult to control due to it being rhizomatous and producing a very large number of tubers (the nuts) on the rhizomes. Halosulfuron-methyl (Group 2, (Sempra®)) is the only herbicide registered to control nutgrass in maize but only offers some control and controls few other weeds.

(Dr Trevor James, AgResearch Ltd., pers. comm.)

3.2 Resistance management

Where any of the weed species listed above are present extra vigilance is essential. Existing herbicide strategies should be thoroughly reviewed, particularly to minimise the use of herbicide groups to which resistance exists or is a risk (as described above).

Integrated weed management is the best strategy to minimise the risk of the evolution of resistance. Ideally this will include using non-chemical approaches such as mechanical weed management (discussed elsewhere in this FAR Focus). Within the herbicide toolbox there are some key strategies to reduce the risk of resistance developing. At the heart of these is increasing the diversity of herbicides.

The highest risk factor for developing resistance is to repeatably use the same herbicide Group, or worse the exact same product. This is exemplified by the wine sector which have repeatably used only glyphosate (Group 9) for under-vine weed management, resulting in very high levels of resistance in multiple ryegrass species across the whole country. The first step of diversification is to use a sequence of different Groups. Then to use tank mixes of different groups. The best option (within the chemical toolbox) is to use a sequence of different mixtures, although this is difficult when the choice of herbicide groups is limited.

Monitoring and correctly identifying the actual weed species present in each crop allows you to select the best herbicide(s) for the weed species present (while taking into account herbicide applications to the paddock over the last two to three years). Then, ensuring optimal application conditions and achieving the best herbicide application via correct rates, tank mixing, pressure, nozzles, etc. is key. Getting all these factors right maximises the likelihood of the herbicide successfully controlling weeds and minimises the risk of resistance.

After application, the paddock must be scouted for survivors. Controlling, or even eliminating, resistant weeds is much easier if they are caught early. Once herbicide resistant weeds are established elimination is likely to be impossible, resulting in more complex and costly future weed management. Put maximum effort into controlling any weed which survive herbicide application, to prevent weed seed shed later in the season. Minimising seed shed / seed rain is a core component of IWM.

3.3 Fence-lines and other uncropped areas

Uncropped areas, such as fence-lines that are sprayed / kept bare are significant herbicide resistance risk areas, particularly where they are repeatedly sprayed with glyphosate (Group 9). Fence-line weeds that develop resistance are likely to move into the crop and be difficult to manage.

The starting approach should be to find alternatives to herbicides for these areas, for example:

- Where fences are no longer useful, remove the fence and plant the area into the crop or pasture. This will provide both competition and a change in weed management practices.
- If possible, raise the bottom wire or do not electrify it, as livestock frequently graze pastures very hard under fence-lines due to less dung and urine being deposited there.
- Leave a narrow strip of existing pasture or introduce other non-invasive but suppressive species such as Phalaris and/or clover, along the fence and then cultivate the rest of the paddock.
- Mow the vegetation along the fence-line, cultivate in the field margins and only use herbicides in the area immediately under the wire.
- Plant the crop or pasture as close to the fence-line as possible to keep uncropped areas to a minimum.

Where herbicide use is essential, then the risk of weeds developing herbicide resistance can be reduced by including other non-glyphosate (Group 9) products in the herbicide programme. For example, alternate glyphosate for one of these herbicides: metsulfuron (Group 2 (Escort®)), amitrole (Group 34), oxyfluorfen (Group 14, (Oxy250SC)), oxadiazon (Group 14, (Foresite®)) or herbicide combinations such as Tag™ G2. NB These chemicals should only be applied to non-cropping areas.

For public areas, e.g. roadsides, if herbicide resistance is suspected then in the first instance contact the responsible authority to discuss the issue, e.g. local / regional council for local roads or NZ Transport Authority Waka Kotahi for national roads. This should include determining what herbicides have been used, if the weeds are truly resistant (which will require glasshouse testing), and what course of action will be taken and by whom. There are various requirements on the authorities for roadside vegetation management, including a maximum height. Many weeds going to seed may well exceed the height requirement and therefore require the authorities to manage them. One potential option for local roads is having no-spray zones, which in many council areas puts the requirement for vegetation management on the adjacent landholder.

4. On-farm biosecurity

Key points:

- Growers have a vital role in preventing new weeds establishing and spreading within New Zealand.
- It is essential to have and implement a biosecurity plan for your property.
- If you find a new weed on your property, get it correctly identified, and contact the relevant authority (see below).
- Weed seeds are moved between properties on farm machinery, clothing and footwear and in animal feeds. Watch out for new weeds on your property after machinery movements and the importation of animal feeds.
- See www.far.org.nz/resources/biosecurity for current biosecurity information.

4.1 Create and implement an on-farm biosecurity plan

Building on the biosecurity issues discussed in the introduction, the key to good on-farm biosecurity is to have a clear plan that is fully understood by all staff and actively implemented.

FAR have produced an arable farm biosecurity register to help you create a clear biosecurity plan, not just for weeds but also pests and diseases. It covers six areas:

- Visitors, e.g. contractors and consultants, and their vehicles, clothing, tools etc.
- Machinery, particularly contractor's.
- Livestock and brought on feed.
- Seed and plant material, including using tested clean seed and detailed record keeping.
- Monitoring for biosecurity incursions, particularly regular crop walks, and what action to take if they occur.
- Good communications with neighbours, contactors, advisors and everyone involved in the farm business.

For more information and to download the risk register see www.far.org.nz/resources/arable-biosecurity-risk-register

Particular issues for weed biosecurity include: the movement of people, machinery, seeds and animal feeds on the farm and develop protocols for reducing these risks. For example:

- Requirements for machinery clean down and movement on and off the farm.
- Requirements for personnel visiting the farm and specific crops.
- Certification of seeds and ensuring clean seed.
- Specifications for imported feeds and moving feed within farm from known weedy areas.
- Undertaking regular crop scouting, particularly at crop establishment when many weeds germinate, but, also towards and before harvest when escaped weeds are larger, easier to identify and before they set seed.
- Procedures for containing an unwanted weed.

4.2 Biosecurity - who to contact?

The Ministry for Primary Industries (MPI) has primary responsibility for biosecurity. In the first instance contact Biosecurity NZ at MPI www.mpi.govt.nz/biosecurity/ 0800 88 99 66 report.mpi.govt.nz/pest/. After contacting MPI / Biosecurity contact FAR www.far.org.nz/contact-us 03 345 5783 or FAR & Seed and Grain Readiness and Response (SGRR) Biosecurity Officer info@sgrr.org.nz

The list of plants that are a biosecurity risk is constantly changing (same for pests and diseases). Check the current status of any weed or other pest you think may be a biosecurity issue. See www.mpi.govt.nz/biosecurity/about-biosecurity-in-new-zealand/registers-and-lists/ for current lists of unwanted and notifiable organisms, or contact one of the biosecurity contacts above for advice.

4.3 Biosecurity classifications

Organisms, including plants, that are considered a biosecurity risk are declared to be Unwanted Organisms. These are defined as organisms that are capable or potentially capable of causing unwanted harm to any natural and physical resources or human health. Unwanted Organisms are then classified as regulated,non-regulated or not assessed.

Regulated: the organism is of potential importance to New Zealand and not yet present here, or present but not widely distributed and being officially controlled. Actions are required to manage any risk of entry and establishment of regulated organisms.

Non-regulated: the organism is either, present in New Zealand, or unlikely to establish, or unlikely to cause significant harm.

Not assessed: the organism has not yet been assessed and given a biosecurity classification.

In addition, Notifiable Organisms are organisms that must be reported to MPI, if spotted in New Zealand.

4.4 Specific biosecurity weeds

A small number of weed species are of particular biosecurity focus in maize growing areas. They are listed in order of importance as determined by FAR's biosecurity officer.

4.5 Velvetleaf *(Abutilon theophrasti)*

At the time of publication velvetleaf is listed as an unwanted organism but it is not notifiable. If you find it on your farm it is essential to contact FAR (see above for contact information).

Velvetleaf has been reported in New Zealand over a number of years but it had been successfully contained and eradicated. However, in 2011 velvetleaf was found well established on a Waikato farm where the grower complained of a weed he was unable to control that was severely depressing his maize yields. In 2012 it was declared an Unwanted Organism. This means all infestations must be reported and eradicated. Tracing farm machinery and silage movements has identified over 60 infested properties in North and South Auckland and Waikato where it is actively being managed by both Waikato Regional Council and Ministry for Primary Industries (MPI). In 2015 velvetleaf was accidently imported as a contaminant in fodder beet seed and sown on more than 600 properties throughout the country. In this case, a grower noticed an unusual weed in his paddock, photographed it and got it identified. The response by MPI undoubtedly saved many more properties from becoming infested by stopping the contaminated fodder beet seed being sown.

The latest New Zealand incursion was reported in a Waikato maize crop. It was spotted by a grower, who took the responsible action of getting the weed identified. Scouting by FAR, the regional council and AgResearch confirmed that the weed was well established both in the crop and along the fence-lines. It was likely that it had been there for more than one season.

Figure 4. Velvetleaf (*Abutilon theophrasti*).

In North America (and increasingly in Europe) velvetleaf has become the foremost broadleaf weed in maize and soy bean crops. If uncontrolled, it can reduce yields by up to 34% and costs the industry hundreds of millions of dollars. It also has evolved resistance to Group 5 herbicides in the USA.

There are regular velvetleaf updates published on the FAR website www.far.org.nz/resources/biosecurity and https://www.mpi.govt.nz/biosecurity/exotic-pests-and-diseases-in-new-zealand/long-term-biosecurity-management-programmes/velvetleaf/. Please check these for current velvetleaf biosecurity information.

4.5.1 Characteristics of velvetleaf

- Velvetleaf is a hot weather, annual weed that grows quickly from seeds which germinate throughout the growing season.
- The fastest growth occurs six to eight weeks after weed emergence and in favourable conditions, velvetleaf plants will grow taller than the surrounding crop.
- Grows 1 to 2.5 metres tall, overtopping most crops, with branched, stout stems covered in downy hairs (Figure 4).
- Large heart-shaped leaves with pointed tips at their ends, which grow alternately on the stem (Figure 4).
- Flowers are yellow and grow up to 2.5 cm in diameter, with five petals attached at the base. The seed heads are distinctive pod-like capsules consisting of 12-15 woody segments that form cup-like rings (Figure 4).
- Shade tolerant and can produce seed and infest a maize paddock while growing under the dense canopy.
- Its only redeeming feature is that it is frost-tender.
- Velvetleaf is self-compatible and pollination occurs on the first day of flowering. The seeds mature one to two weeks later and each plant can produce up to 35,000 seeds. Seeds will continue to ripen on the plant after it is pulled out.
- Seeds have a hard coat and can remain dormant in the soil for 50 - 60 years. An AgResearch study of the weed seedbank at a highly infested site has shown the emergence of velvetleaf has not diminished after five years, despite four to five repeat cultivations over the summer to stimulate seed germination. Comparatively, there are very few other weeds left at the site.
- Velvetleaf seed can also survive in silage for more than three months and remain viable after passing through the digestive tracts of animals including poultry.

4.5.2 Management measures

If you suspect you have found velvetleaf on your farm, do not remove the plants, photograph them, mark their location, and immediately contact FAR (see above for contact information).

Where velvetleaf has been confirmed on your farm, scouting and roguing is the first option for control, but will only be successful if weed numbers are small and the plants are destroyed after removal.

Because velvetleaf germinates throughout the season it is difficult to control with herbicides. Successful control depends on spraying it at the 2-4 leaf stage because it becomes very difficult to kill once the stems harden. Overseas research has shown that pre-emergence applications of atrazine (Group 5) have variable success rates and it has developed resistance to atrazine in the USA. Other active pre-emergent herbicides such as saflufenacil (Group 14) should be used as well. Due to the prolonged germination period pre-emergence herbicides must be followed with post-emergent treatments. For example, at least two post-emergence applications of mesotrione (Group 27), dicamba Group 4 and/or topramezone Group 27 will also be required. Plant size, application rate and choice of adjuvant are critical for success. Post-emergent herbicides have little residual activity on velvetleaf and do not suppress further germinations. It will be necessary to continue a post-emergent programme, regular monitoring and hand roguing throughout the season to control velvetleaf.

See also FAR Arable Extra 113 Velvetleaf in maize for more detailed information including management options https://assets.far.org.nz/blog/files/abdc73e2-caa7-463d-b395-1778453010d7.pdf

4.5.3 Case study - velvetleaf

A Whanganui grower has about 100 ha of maize grain and 40 ha of grass for beef cattle on fertile river flats. Velvetleaf was in a paddock when he bought the property, coming in on a contaminated fodder beet seed line in 2015. "I believe the initial infestation was about 30 plants in fodder beet which were hand pulled."

For the first two seasons he cropped the whole property in maize, apart from the area where the velvetleaf had been found, which was fallowed. For these two seasons this area was lightly cultivated, with any regrowth sprayed. However, as the area was in the middle of a 24 ha cropping block, it wasn't practical to leave it, so the grower began cropping it.

"I treat the whole 24 ha as if it has velvetleaf," he says. He carries out a post-emergence spray of herbicide Arietta® (Topramezone Group 27) and walks the maize to check for velvetleaf. "When I plant that area, I try to make it the last planting of the season and then wash down all the gear. This is also done with the harvester." As velvetleaf can germinate throughout the season, it can be difficult to spot and control in a growing maize crop.

Horizons Regional Council staff visit with velvetleaf sniffer dogs about three times during the season, sometimes making a final check once the crop is harvested. Any velvetleaf found is GPS marked so authorities and the grower know exactly where the sites are. While two or three plants were found when the patch was being fallowed and lightly cultivated, none were found for four years, until one small plant was found by a sniffer dog in February 2024. The grower is confident that chemical control, crop walking and the sniffer dogs should kill or identify any velvetleaf early. "I can't really afford to leave that piece of ground out of maize".

"Being a grain grower, we need to be more vigilant and proactive with our weed control, compared with maize silage". This is because with grain crops the longer time to harvest means velvetleaf plants germinating after the post-emergent spray could get to maturity and drop seed, whereas silage crops are generally harvested before this can occur. "We like to have nice clean crops. I walk our paddocks quite often, until they get too high to do so".

4.6 Yellow bristle grass *(Setaria pumila)*

At the time of publication, yellow bristle grass is not listed by MPI Biosecurity, as it is now present throughout the North Island and also in Nelson, Marlborough and Canterbury. It is primarily a farm level biosecurity issue and is becoming an increasingly troublesome weed. Weed distribution models indicate that it will grow in all farmed areas.

First noticed in pastures as it was avoided by grazing cows, it is believed to have initially spread along roadsides by mowers and vehicles but soon infested maize crops where it was spread over large distances on silage machinery. It is a prolific seed producer, so within a few years it can become the dominant pasture species and an important weed in maize. It is particularly invasive in Waikato, Taranaki, Bay of Plenty and South Auckland.

4.6.1 Characteristics of yellow bristle grass

- A summer annual C4 grass which reproduces only by seed.
- An upright annual grass growing 25 - 45 cm high, although in open pasture its first leaves are typically parallel to the ground (Figure 5).
- The leaves are yellow-green to green in colour and usually red or purple at the base. They are flat, hairless, soft and twisted. The leaf sheath is flattened. There are no ears (auricles) at the junction of the leaf blade and sheath.
- The seed head is a cylindrical 'spike', 2.5 - 10 cm long. It consists of many densely packed spikelets, with each spikelet bearing a single seed. At the base of each spikelet are five to ten bristles, 5 - 8 mm long. Initially the bristles are green, but soon change to a golden-brown. It is the colour of these bristles that give the grass its name (Figure 5).
- Optimal air temperatures for germination are 16°C and 35°C (mid-October to mid-January).
- Early seed heads appear in late December and are produced throughout summer.
- Most seeds near the soil surface survive for only a few years under field conditions.
- Seeds eaten by livestock survive digestion and are deposited in dung. They can survive for up to three months in effluent ponds and will be spread around the farm in effluent.
- They do not compete with strong ryegrass pastures but will establish in any gaps within the pasture, especially old dung pats.
- Yellow bristle grass is commonly found in maize silage crops but seed in sealed silage has a low survival rate with germination reduced to zero after one week.
- Seeds may be spread from affected properties to clean ones through livestock movement, feed such as hay, roadside grazing, farm machinery, and along roads by vehicles and road work machinery.

Figure 5. Yellow bristle grass (*Setaria pumila*).

4.6.2 Management measures

The most important control mechanism is preventing seed set, as yellow bristle grass plants are frost sensitive and only survive the winter as seed.

Small infestations can be treated with glyphosate at all growth stages but the seeds will not be killed. Where seeds have set, manual removal and destruction of plants is a good option. Ensure the bare areas are immediately resown with vigorous competitive pasture, particularly in the main germination period of October to January.

Yellow bristle grass can be controlled in pasture with two selective herbicides, fenoxaprop-P-ethyl (Group 1, Puma® S) and asulam (Group 18, Dockstar™). However, these herbicides cannot be used in maize crops. Headland infestations can be managed by planting a strip of competitive pasture or other suppressive species in the infested area and confining the above herbicides to the strip area.

Post-emergence applications of nicosulfuron Group 2 or topramezone Group 27 to the outer headland rows of the maize crop will generally be effective at removing yellow bristle grass and other grass weeds that are moving in from paddock margins. However, new germinations may occur after rain, requiring additional herbicide applications for control and minimising weed seed rain.

For detailed information on yellow bristle grass see: "Yellow bristle grass: The Ute Guide. Third Edition." https://assets.far.org.nz/blog/files/f5590c48-61a2-5e85-9be4-ab1613365e3a.pdf

4.7 Black-grass *(Alopecurus myosuroides)*

At the time of publication, black-grass is a regulated and unwanted plant but is not notifiable. However, as described below it poses a very high risk to New Zealand arable systems. If you suspect you have black-grass on your farm, do not disturb the plants, take photos, particularly of the seed head, with the location, and immediately contact MPI, FAR and/or SGRR (see above for contact details).

Black-grass is an increasingly problematic weed in places such as Northern Europe. It has resistance to multiple herbicide groups, so incursions are likely to come with herbicide resistance 'built in' making their elimination and management even more challenging. It is among the highest priority weeds to be kept out of New Zealand.

Black-grass is an annual, slender grass growing up to 80 cm high, often in tufts. The leaves are hairless, leaf sheath is smooth and green to purplish in colour. The leaf blade is pointed, 3 to 16 cm long, 2 - 8 mm wide, green, and rough in texture. The spikelets are cylindrical, yellow-green, pale green or purple in colour, and vary from 1 - 12 cm long (Figure 6). The common name black-grass derives from the dark colouration shown by ripening seed heads.

Individual black-grass plants produce 2 to 20 heads per plant, and 80 to 150 seeds per head. The seeds have a short dormancy period of several weeks. Black-grass germination is stimulated by light and the optimum soil temperature for germination is 15°C. Black-grass seedlings only emerge from seeds within the top 5 cm of soil. Buried seed (e.g. by ploughing) has a survival rate of 20 - 30% per year, so after three years burial only about 1 - 3% of seeds will be viable. However, it can remain dormant / survive for up to 11 years. On-property eradication of black-grass is a three to five year project.

See the FAR update on black-grass for more information assets.far.org.nz/blog/files/a3a46217-eb56-5792-a482-f2ee067a8be2.pdf

Figure 6. Black-grass (*Alopecurus myosuroides*).

4.8 Palmer amaranth *(Amaranthus palmeri)*

At the time of publication Palmer amaranth is regulated but not notifiable. If you think you have Palmer amaranth, do not disturb the plants, take photos for identification, record the location and contact FAR and/or SGRR (see above for contact details).

Palmer amaranth looks similar to redroot pigweed (Amaranthus retroflexus) which is a common weed, but Palmer amaranth will grow much larger. It is a large erect plant reaching heights of up to two metres. Stems and leaves have few or no hairs. Petioles are often longer than the leaf blade. Leaves occasionally have a V-shaped, 'thumb-print'. The terminal flowers can reach lengths of 30 to 60 cm. Plants are highly variable in shape (Figure 7).

Palmer amaranth is considered high risk as there is a clear entrance pathway through second hand headers / harvest machinery. Overseas it is resistant to herbicide Groups 2, 3, 4, 5, 6, 9, 10, 14 and 27, so were it to enter the country it is highly likely that it would come with resistance and therefore be very difficult to manage with herbicides.

Figure 7. Palmer amaranth (*Amaranthus palmeri*).

4.9 Alligator weed *(Alternanthera philoxeroides)*

At the time of publication alligator weed is listed as regulated and unwanted, so must be notified to MPI Biosecurity if found, and then your local and/or regional council as well as FAR and/or SGRR (see above for contact details).

Enact strict site level biosecurity to prevent its spread to other farm areas. Keep stock out of infested areas and minimise all other activities that could cause the plants to fragment and disperse, especially along waterways.

Alligator weed is an invasive pest plant that is easily spread but very costly to manage. Originally from Brazil, it is thought to have arrived accidently in New Zealand in the early 1900s and has now spread to parts of northern New Zealand.

It is a fast and low-growing, non-woody perennial plant. Leaves are bright green and waxy. They are between 5 - 10 cm long, up to 2 cm wide, and arranged in opposite pairs on the stem. The white flower looks like a small clover flower and is at the end of a longish stalk. Stems are thick, soft, and hollow, often with a reddish tinge (Figure 8). It is able to grow on both land and on water where it forms dense floating mats. It's tolerant of brackish sites when growing in flowing waterways. It can block waterways, aggravating flooding and impeding access. In pasture, it can out compete more favourable plants and be harmful to animals.

In the Waikato region, alligator weed is found mainly at sites on the margins of, and in, the Waikato River, on the edges of some harbours (e.g. isolated sites in Kāwhia), on farmland, in wetlands, in market gardens and on urban properties. It is also present at sites along the margins of other waterways, near Waihi and Waikino, and has become a significant problem in new subdivisions in Hamilton city. New sites have recently appeared along some west coast beaches and on the Coromandel Peninsula.

Figure 8. Alligator weed (*Alternanthera philoxeroides*).

4.10 Broom corn millet *(Panicum miliaceum)*

At the time of publication, broom corn millet is not listed as either notifiable or unwanted by MPI. It is therefore an individual farm biosecurity risk.

Broomcorn millet is one of the world's oldest cultivated cereals. Today it is widely grown in the northern hemisphere for human consumption and bird seed. In 1970, a wild biotype with black seeds emerged and quickly became weedy, producing more dry matter, reaching a greater height and producing twice as much seed. This bio-type has become a persistent weed problem on cropping land.

The first reported incidence of this plant in New Zealand was in a domestic garden in Marlborough, where it is thought to have grown from bird seed. It is unfortunate that it was not controlled at this point, as from there it spread into local sweetcorn crops and then rapidly dispersed into other regions (most likely by harvesting machinery). It is now a major weed in sweetcorn crops in Marlborough, Hawke's Bay and Gisborne, and has also been reported in maize crops in these regions.

4.10.1 Characteristics of broom corn millet

Broom corn millet is an annual grass with fibrous roots and branched stems 0.5 - 1.5 m tall, either spreading or erect. Leaves and especially leaf sheaths are covered with dense stiff hairs. Figure 9.

- Reproduces by seeds.
- Fast growing and can set viable seed within six weeks of emergence.
- Shallow roots and very low water requirements i.e. can grow well in dry soil.
- Strongly competes with the crop for water, nutrients and sunlight.
- Seed is extremely hardy and able to survive for long periods.
- Plants can emerge from seed buried as deep as 12 cm, and in some soils as deep as 17 cm.
- Germination occurs between air temperatures of 13°C to 34°C, and New Zealand testing found the highest germination rates were between 27°C and 34°C.
- Most seed near the soil surface will germinate at the first opportunity.

Figure 9. Broom corn millet (*Panicum miliaceum*).

4.10.2 Management

If broom corn millet is present on or around your farm, it is important to keep a watch for it, and if it is found, prevent it from setting seed. The most likely seed transfer among farms and paddocks is on farm machinery, especially harvesters, but multiple sources are likely, e.g. brought on feed such as straw, livestock etc.

Despite being able to emerge from depth, deep burial reduces its competitive ability with the crop, as this reduces the vigour of the seedlings.

Pre-emergence herbicides only provide two to three weeks residual activity so are unlikely to control late germinating broom corn millet, meaning a post-emergence herbicide programme is likely to be required. Post-emergence herbicide applications must be timed to catch the plants when they are young, once the stems start to become woody efficacy will decrease significantly. In a Hawke's Bay trial, excellent control of the weed was obtained with a single post-emergence application of nicosulfuron, following a pre-emergent (Table 5). In contrast, in a Gisborne trial, two post-emergence applications were required, timed three weeks apart, each a week after heavy rain (Table 5).

Table 5. Herbicide treatments used for broom corn millet control in sweetcorn in trials in the Hawke's Bay and Gisborne.

Region	Pre-emergent programme	Post-emergent Programme	Level of control
Hawke's Bay	Atrazine @ 0.6 kg a.i. /ha + Acetochlor @ 2.5 kg a.i. /ha Applied 8 November	Nicosulfuron 60 g a.i. /ha + surfactant 0.5% Applied 4 December	100%
Gisborne	Glyphosate @ 540g a.i. /ha. Applied 15 December	Nicosulfuron 60 g a.i. /ha + surfactant 0.5% Applied 4 January Reapplied 24 January	100%

4.11 Madagascar ragwort *(Senecio madagascariensis)*

At the time of publication Madagascar ragwort is not listed by MPI as a biosecurity issue. It is currently only present in Northland and is primarily a weed of pasture, but, where maize is rotated with pasture it has the potential to infest those crops. As it is poisonous to a range of livestock its presence in silage maize crops is of particular concern. It is therefore an individual farm biosecurity risk.

Called fireweed in Australia it is one of the worst weeds of south-eastern coastal pastures, which have a similar climate to New Zealand, indicating its potential to become an increasingly problematic weed here.

Madagascar ragwort is a perennial, erect, smooth stemmed, herbaceous species that grows up to 20 - 60 cm in length. It may become woody and shrub-like in appropriate conditions. Leaves are alternate, narrow-lanceolate to elliptic in shape, usually bright green, smooth with margins that are lobed, serrate or entire. The broader, larger leaves are stem clenching and fleshy, 2 - 7 cm long and 3 - 10 mm wide. The flower head is daisy like (it is a member of the sunflower family) small, yellow and 1 - 2 cm in diameter (Figure 10).

Figure 10. Madagascar ragwort (*Senecio madagascariensis*).

4.12 Noogoora bur *(Xanthium occidentale)*

At the time of publication Noogoora bur is not an MPI Biosecurity listed plant, but, it is a 'Controlled Area Notice' weed in the Hauraki Gulf where it is a under a whole region progressive containment order from the Auckland Reginal Council. It is also known to be present in other North Island areas, such as the Hawke's Bay, and is likely to be wider spread. You must not plant, breed, distribute, release or sell Noogoora bur within the Auckland region. All instances of Noogoora bur anywhere in the Auckland region, must be reported to Auckland Regional Council at pestfree@aucklandcouncil.govt.nz.

Noogoora bur is an annual herbaceous species < 2.5 m tall with a shallow taproot. Stems are blotchy purple and hairy. Leaves are large and serrated, with dark green tops and pale green undersides. Flowers are small and yellow. Burs are small, hard, brown, woody and hooked (Figure 11).

Figure 11. Noogoora bur (*Xanthium occidentale*).

5. IWM Monitoring and evaluation

Key points:

- Regular monitoring of crops is central to integrated weed management.
- Monitoring should occur throughout the life of the crop, particularly for biosecurity and herbicide resistant weeds.
- Monitoring at establishment is key for choosing the best herbicides.
- High risk areas, e.g. gateways, headlands, where machinery starts operating should be more intensively monitored.

Regular monitoring / scouting of crops is the heart of the IWMPRAISE integrated weed management framework (Figure 2). You cannot manage what you're not measuring! Regular monitoring / scouting of crops is important to detect weeds that are a biosecurity risk and for the early identification of herbicide resistance.

There are no hard and fast rules on how to monitor crops (including maize) for weeds, so common sense and cropping experience are the main guides.

5.1 When to monitor

Monitoring is based on having good paddock level records of previous years' crops, the herbicides used and any particular weed issues that occurred.

Clearly, pre- and post-crop establishment are key times for identifying the weed species. The weed species present will inform decisions on what herbicides and non-chemical control measures to use. Always take into account previous years' herbicides so different groups are used, and also consider which weeds are at higher risk of resistance (see Section 3). After application, check that the herbicides, and other weed management measures, actually worked. If weeds survive, and especially where the species and distribution of weeds points to resistance (see Section 3.2), taking additional action to control such survivors is essential.

The period approaching canopy closure is another key monitoring time. The crop will still be small enough to walk through and see weeds that are at or close to canopy height. This is a key time for detecting biosecurity weeds, particularly those that germinate across the warmer months (such as velvetleaf).

The crop should then be scouted as harvest and/or senescence approaches. This will be more difficult in silage crops than grain crops. Technology (see below) may be of help. This is another important time for detecting biosecurity weeds so action can be taken before harvest, to prevent them going to seed.

Harvest machinery operators should be briefed on biosecurity weeds of concern that they may be able to spot from the cab. Ideally where they are seen they can be driven around and not harvested. Plants should then be notified and/or destroyed as appropriate for the species. All the information from these monitoring events should be noted in farm records.

5.2 Where / how to monitor?

Ideally the whole crop would be walked at each monitoring event, but, this is often not possible due to time constraints and the difficulties of actually physically walking through a mature crop. Technology (see below) will be of increasing help here. Targeting the higher risk areas is therefore important, these include:

- Risk areas identified in previous years, e.g. suspected resistance.
- Gates where machinery enters and the area of the paddock where they first start working. Seeds contaminating machinery are more likely to be deposited in the first 100 m or so of where machinery starts working. Harvesters can carry seed further.
- Headlands, and field margins as a whole.
- Randomly picking a handful or two of rows (depending on the size of the paddock) and walking them, looking on both sides as much as crop size will allow.

5.3 Monitoring technology

Increasingly sophisticated technology is being developed for weed monitoring and detection. However, most of this is still at the research and development stage, so is not yet a reality in New Zealand. In tall, high biomass crops such as maize, that are difficult if not impossible to physically move through post canopy closure, drones (unmanned aerial vehicle, UAV) with camera systems can fly over the crop and identify large weeds, such as velvetleaf and Palmer amaranth, that will overtop maize.

6. IWM- Prevent weed establishment

Key points:

- Establishment is the first of the three weed life cycle stages considered in an integrated weed management system.
- Diversifying rotations is an increasingly important weed management strategy.
- Cover cropping can support weed management.
- Over winter cover crops turned into surface mulch in spring can achieve significant weed suppression, allowing for a single post-emergence herbicide to be used, so helping to address the risk of herbicide resistance.

Preventing weeds establishing is the first step in the IWMPRAISE weed life cycle management approach (Figure 1). Traditionally this is also where most current herbicide based weed management is focused with pre- and post-emergent herbicides. However, IWM takes a wider approach; it is about stepping back and thinking about the farm system as a whole and the five IWM pillars (Figure 2).

Diversifying the farm system is one of the most effective weed, pest and disease management tools available. It is not always cheap or easy, but as biosecurity breaches and herbicide resistance become more common, it starts to make sense. The three key diversification strategies to reduce weed establishment are rotations, cover crops and field margin management.

6.1 Rotations

In the 1938 Yearbook of Agriculture Clyde E. Leighty wrote "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." The date of 1938 is key - this was the modern pre-herbicide era, so in the time before modern herbicides, rotations were seen as a key weed management tool. As herbicide options decrease, rotations will become increasingly important.

There are no hard and fast rules for diversified rotations but key approaches include:

- Including both broadleaf (dicot) and grass (monocot) crops,
- Maximising the number of different crops grown,
- Growing both autumn and spring sown crops,
- Including a pasture phase, of a year or more.

The greater the biological differences between crops, the bigger the benefit. This is because firstly, biologically different crops compete with weeds in different ways and secondly, allow the use of different herbicide groups. Changing between spring and autumn sown crops can provide large benefits, while the best results come from rotating between grazed pasture and annual crops. Just a couple of years under pasture will result in a considerable decline of the annual weed seedbank, plus a wealth of other benefits such as pest and disease suppression and improved soil organic matter and nitrogen levels. Likewise, the cropping phase eliminates livestock internal parasites, and many perennial pasture weeds. While a fully diversified rotation is ideal, it is not always possible due to practical and financial limitations. However, any rotational diversification is better than none. Where continual maize is the only option, cover crops provide another form of rotational diversification.

6.2 Cover crops

Key points:

- Cover crops provide a wide range of benefits.
- Typically, annual arable and pasture species such as cereals and legumes are used as cover crops.
- The most common use of cover crops is as an alternative to winter fallow, to protect soil, fix nitrogen, smother weeds and reduce nitrate leaching.
- A five-year trial at FAR's Northern Crop Research Site researched the potential for over winter cover crops to suppress weeds in the following no-till maize grain crop.
- Cover crops achieved good weed suppression in the absence of herbicides.
- Legume cover crops increased maize grain yield more than non-legume cover crops, most likely due to their nitrogen fixation, despite having slightly lower weed suppression.
- Combining cover crops with one post-emergent herbicide application achieved good weed management while maintaining yield.
- These results apply to a no-till system with retained residue and a later planting date.

6.2.1 Introduction

"Cover crop" is an umbrella term for crops grown to provide a range of benefits to the farm system and environment other than cash income. These include: weed suppression, protecting soil from rain and wind erosion and over-heating by sunlight, reducing nitrate leaching, improving soil quality through organic matter returns and increased microbial activity, nitrogen fixation by legumes, and pest and disease management.

Where cover crops have a specific purpose their names typically describe that purpose. For examples, "catch crops" are grown to capture nitrate and reduce leaching, "smother crops" are grown to produce a large amount of above ground biomass to smother weeds. The name 'service crop' is increasingly being used in Europe as an alternative overarching term for cover crops. When discussing cover crops the term "cash crop" is used to describe the crop being grown for sale or generate direct income of some sort, e.g. silage for livestock feed.

A wide range of plant species are used in cover crops in annual cropping systems. Typically, they are annual arable and pasture species, for example, cereals such as oats and ryecorn, legumes such as clovers and faba beans, grasses such as annual ryegrass, and brassicas such as mustard. Species are often chosen for particular attributes, for example quick emergence, rapid ground cover, fixing nitrogen, and taking up soil nutrients all of which can improve crop growth, yield and profit. Cover crop mixtures are often used to gain a range of attributes.

Traditionally cover crops are sown after cash crop harvest in autumn, with their main purpose being to cover the soil - as opposed to a bare fallow - to protect it from the weather. They are then killed and cultivated into the soil in spring, prior to establishing the next cash crop.

6.2.1.1 Why do arable growers use cover crops?

In 2021, FAR conducted a survey of arable growers using cover crops. It was completed by 42 growers from eight regions, mostly Canterbury and Waikato. The survey sought to understand the reasons growers were using cover crops, how they were being used and where further research might be required. Table 6 shows growers' short-term and medium to long-term drivers for using cover crops.

The survey showed that growers are using cover crops for a diverse range of purposes (Table 6). Protecting and improving soil health and nutrient management were the main drivers; these align with the traditional use of cover crops. Improving biodiversity coupled with pest management (by increasing beneficial insects) were the next group of drivers, while the final cluster focused on managing weeds, reducing herbicide use and reducing the risk of herbicide resistance.

6.2.1.2 What role do cover crops play in IWM?

Internationally, cover crops play an important role in integrated weed management. Their benefits include:

- Directly competing with weeds, thus preventing weeds going to seed, or significantly reducing seeding.
- Once established, inhibiting further weed seed germination.
- Providing habitat for beneficial insects, such as carabid beetles, which feed on seeds.
- Allelopathic cover crops prevent seeds from germinating and directly kill some weed seedings.
- If intercropped - grown with a cash crop - they cover the ground and suppress weeds, for example clover growing under maize.
- Controlling difficult to manage perennial weeds by smothering them with very large amounts of biomass and / or a thick layer of residue / mulch that suppresses weed germination and kills emerging weeds by blocking sunlight.

A key aspect of most cover crops for weed management is to minimise weed seed rain and thereby reduce the weed seed bank, which is a critical component of integrated weed management.

An important contrast between cover crops and herbicides is that cover crops always provide multiple services, e.g. weed suppression and soil health benefits, while herbicides just kill weeds. Mostly, these services are beneficial so it can be valuable to consider other benefits such as nitrogen fixation or pest management.

While cover crops have many benefits, there are also challenges to their use. Cover crops are still crops, so there are costs associated with seeds, establishment and management (Table 7). The benefits thus need to outweigh the costs.

The impact of cover crop species on the wider rotation and neighbouring farms also needs to be considered in terms of issues such as hosting pests and pathogens (e.g. acting as a green bridge), and if allowed to flower, pollen contaminating neighbouring seed crops.

Table 6. The top seven, short-term and medium to long-term, drivers of arable growers for using cover crops.

Priority	Short-term drivers	Medium to long-term term drivers
1	Return organic matter to the soil	Build system resilience
2	Avoid fallow periods	Improve nutrient cycling and reduce nitrate leaching
3	N capture and cycling to the following crop	Reduce soil compaction
4	Reduce leaching	Increase biodiversity
5	Break up disease cycle	Reduce need for and cost of inputs e.g. agrichemicals
6	Reduce soil loss	Reduce weed seed bank
7	Weed suppression / attract beneficial insects for pest management	Decrease risk of herbicide resistance

Table 7. Indicative example of cover and catch crop species comparisons from FAR Crop Action, Issue 7, 2024.

Type	Species	Seed size	Seed price/kg	Seeding rate (kg/ha)	Planting depth (mm)	Dry matter yield (t/ha)	Suitability for grazing	Suitability for silage
Grasses	Annual ryegrass	•	$	20 - 30	10	3.0 - 6.0	Excellent	Excellent
	Cereals	●	$	80 - 150	20 - 40	4.0 - 9.0	Good	Excellent
Legumes	Faba bean	⬤	$	200 - 300	50 - 70	3.0 - 7.0		Good
	Vetch	●	$ $ $	25 - 40	20 - 40	2.0 - 5.0	Adequate	Good
	Lupins	⬤	$ $	100 - 150	40 - 60	3.0 - 6.0		
	Annual clover	·	$ $ $	4 - 10	5 - 10	2.5 - 5.0	Good	Excellent
	Perennial clover	·	$ $ $	4 - 10	5 - 10	0.5 - 1.5	Good	Excellent
Brassicas	Radish	●	$ $	6 - 8	20 - 30	3.0 - 7.0		
	Mustard	•	$ $	6 - 8	10 - 20	3.0 - 6.0		
	Turnips	·	$ $ $	1 - 3	5 - 10	3.0 - 7.0	Good	

6.2.2 Cover crop trial to reduce herbicide inputs and manage herbicide resistance

FAR has undertaken a range of research projects on the use of cover crops for weed management. A key piece of this work was a five-year trial in continual, spring planted, no-till, maize grain crops which investigated the use of autumn sown cover crops to create a weed suppressing mulch in spring to reduce herbicide applications, decrease costs and reduce the risk of herbicide resistance. The trial design is described below and the results are included in a wider discussion of the role of cover crops for weed management in maize.

6.2.2.1 Experimental design

The trial was undertaken by FAR and AgResearch. It was established in June 2016 at the FAR Northern Crop Research Site (NCRS) at Tamahere, near Hamilton. The overall approach of the trial was to plant an over-winter cover crop in late May to early June several weeks after maize grain harvest in early May. The maize stover was chopped and left on the field, which resulted in a build-up of residue over time, leading to difficulties establishing small seeded cover crops in the third year. The cover crops grew through winter and, were terminated in spring by crimper rolling and herbicides. Maize was no-till drilled within a few days of cover crop termination. At maturity six metres of row was manually harvested for grain. To study the cumulative effects the cover crop and herbicide treatments were kept in the same plots for the full five years of the trial.

The trial compared four cover crops, an overwinter bare fallow, and five herbicide treatments in a two factorial criss-cross design with plots of 6 m x 6 m.

The cover crop treatments were:

- Gland clover (*Trifolium glanduliferum*) cv Prima, replaced with hairy vetch (*Vicia villosa*) cv. RM4 in the final (2020-21) season;
- Faba bean (*Vicia faba*) cv Ben;
- Oats (*Avena sativa*) cv Milton;
- Italian ryegrass (*Lolium multiflorum*) cv Tama, replaced with blue lupin (*Lupinus angustifolius*) cv unknown and mustard (*Sinapis alba*) cv unknown, mix in the final (2020-21) season;
- Bare winter fallow - no cover crop control.

The cover crops were chosen for a range of properties, for example, legumes fix nitrogen while grasses are highly competitive.

Gland clover is an annual legume so it fixes nitrogen. It also has good winter growth, a branching habit that covers the soil, is tolerant of mild frosts, and is able to perform in dry conditions across a wide range of soil types.

Hairy vetch is a commonly used as an over winter cover crop in New Zealand. It is an annual legume so also a nitrogen fixer, with long scrambling stems that create good ground cover, it is very frost hardy and also tolerant of dryer conditions.

Faba beans, (often called tic beans when grown as a cover crop), are small seeded cultivars of the cash crop broad bean. Faba bean is a common annual overwinter cover crop. It is frost hardy and a good nitrogen fixer, with an upright growth habit, potentially reaching 1.5 m tall with medium levels of biomass production.

Oats are the most cold-tolerant of the cereals, growing at temperatures as low as 4°C, growing to over one metre tall and producing a large amount of biomass means they are strongly competitive. Seed is readily available.

Italian ryegrass, also called annual ryegrass, is a quick growing grass, with medium biomass production, that forms a dense layer of competitive foliage. As with oats, seed is readily available.

Blue lupin is a cool season annual legume and thus nitrogen fixer. It has a vertical stem growing to around one metre high, a strong taproot that can help break up compaction, but it is intolerant of waterlogging.

Mustard is a broadleaf, growing rapidly up to 1.5 metres on a single stem. Its large leaves it can smother out weeds. Like lupin it has a strong taproot, and like the grasses is an effective nutrient scavenger.

The clover and ryegrass were replaced in the final season due to the build-up of maize stover residue inhibiting emergence of these two smaller seeded cover crops. Sowing rates are listed in Table 8.

The five herbicide treatments included both pre- and post-emergence applications as follows:

Treatment 1 = No herbicide - null control,

Treatment 2 = Pre-emergence herbicide,

Treatment 3 = Pre- and post-emergence herbicide,

Treatment 4 = Single post-emergence herbicide,

Treatment 5 = Both an early and a late post-emergence herbicide.

Table 9 gives the details of the herbicides and their exact timings.

As one of the cover crop treatments was a null control of bare fallow, and one herbicide treatment was a null control of no herbicides, there was a full null control treatment that had no cover crops and no herbicides. This also means that there were cover crops without herbicides, and bare fallow with herbicides, allowing full comparison of all the treatments.

Table 8. Cover crop sowing rates and cultivars (cv) in a trial of overwintered cover crops in maize at the FAR Northern Crop Research Site, Hamilton, from 2016 to 2021. cv n/a = cultivar name not available.

Cover crop	Gland clover cv Prima	Faba bean cv Ben	Oats cv Milton	Italian ryegrass cv Tama	Hairy vetch cv. RM4	Blue lupin cv n/a	Mustard cv n/a
Sowing rate (kg/ha)	6.6	300	100	25	30	60	4
Seed weight	0.7 mg	60 g	35 mg	2 mg	30 mg	180 mg	6 mg
Approx. plant population/ha	3,300,000	5,000	2,900,000	12,500,000	1,000,000	330,000	660,000

The vetch used in the trial was named as Woollypod vetch (*Vicia eriocarpa*) cv. RM4 from Barenbrug, Australia. However woollypod vetch is a name not used in NZ and *Vicia eriocarpa* is not known to be in NZ. The species used has been clarified as 'hairy vetch' (Vicia villosa). In Australia the common name for *Vicia villosa* is 'woolly pod vetch'.

Table 9. Herbicide treatments, timing, and rates of application in a trial of overwintered cover crops in maize at the FAR Northern Crop Research Site, Hamilton, from 2016 to 2021.

Cover crop	Pre-emergence	Post-emergence		
	-1.3-fzz0 WAE	1.9-2.6 WAE	3-3.7 WAE	5.1-5.7 WAE
1	N/A	N/A	N/A	N/A
2	Acetochlor + saflufenacil	N/A	N/A	N/A
3	Acetochlor + saflufenacil	N/A	N/A	Topramezone + atrazine[2]
4	N/A	N/A	Topramezone + atrazine[2]	N/A
5	N/A	mesotrione + atrazine[3]	N/A	icosulfuron

WAE, weeks after maize emergence. N/A, no herbicide applied.

[1] Applied with Hasten™ 0.5% v/v.

[2] Applied with Synoil™ 1% v/v.

Acetochlor, Group 15 (Roustabout®) 840 g/L, 2520 g ai/ha, saflufenacil, Group 14 (Sharpen®) 700 g/kg, 105 g ai/ha, topramezone, Group 27, (Arietta®) 336 g/L, 66 g ai/ha, atrazine, Group 5 (Atraflo) 500 g/L, 500 g ai/ha, mesotrione, Group 27 (Callisto®) 480 g/L, 96 g ai/ha, nicosulfuron Group 2 (Astound® Ultra) 40 g/L, 600 g ai/ha.

Table 10. Maize cultivar, sowing and harvest dates in a trial of overwintered cover crops in maize at the FAR Northern Crop Research Site, Hamilton, from 2016 to 2021.

Season	Maize cultivar	Maize sown	Grain harvest	Cover crop sown
2015/16	N/A	N/A	Start of trial	24 Apr 15
2016/17	Pioneer® 9911	27 Oct '16	2 May '17	11 Jun '17
2017/18	Pioneer® P0021	6 Nov '17	8 May '18	29 May '18
2018/19	Pioneer® Plenitude	9 Nov '18	8 May '19	22 May '19
2019/20	Corson PAC343	7 Nov '19	None	20 May 20
2020/21	Corson PAC343	17 Oct 20	15 Apr 21	End of trial

The maize was drilled in late October to early November (Table 10) a few days after cover crop termination. This is later than maize crops are typically sown in the upper North Island. It was drilled with a John Deere Max-Emerge™ unit equipped with front residue cleaners along with one spiked and one smooth closing wheel at 90,000 seeds/ha with rows crosswise to the cover crop strips.

Cover crops were sown between three and four weeks after the maize grain harvest (Table 10) with a John Deere 750A box drill. There was no harvest in 2020 due to COVID-19 lockdown requirements.

Where cover crops were higher than the effective sprayer height they were rolled with a crimper roller at minimal pressure. The same or next day the cover crops were terminated using glyphosate Group 9 (Weedmaster® TS540) herbicide at rates between 3-4 L/ha, with Pulse® Penetrant added at 0.1-0.2% v/v.

The site was fertilised following industry standards. In the first four seasons a YaraMila™ compound fertiliser (NPK 12:5:15) was applied at planting at rates from 150 to 160 kg/ha in spring and a stabilised urea fertiliser (SustaiN®) was broadcast at rates ranging from 92 to 160 kg N/ha around three weeks after maize emergence. In the final year (September 2020), SustaiN® and sulphate of ammonia were broadcast at rates of 70 and 30 kg/ha, respectively, then two weeks later, a further base fertiliser blend containing 50% MOP (muriate of potash), 25% Calmag, and 25% NRich Ammo 36N was applied at 600 kg/ha. A side-dressing of SustaiN® was applied at a rate corresponding to 125 kg N/ha after maize emergence.

6.2.3 Understanding the mechanisms of weed suppression by cover crops

The management effect of cover crops is often described as 'suppressive'. This contrasts with the effect of herbicides which is described as 'control'. This is because herbicides directly kill i.e. control weeds, while most cover crops do not; rather they suppress them through multiple mechanisms, e.g. competition and reducing soil temperatures. The aim of integrated weed management is not always to completely eliminate weeds (as is the case with herbicides), rather it is to manage them to sufficient levels that they i) do not negatively impact the current crop and ii) minimise weed seed rain to prevent an increase in the weed seedbank.

6.2.3.1 How cover crops suppress weeds

Cover crop residue

For cover crops to provide sufficient residue for weed suppression they primarily need to produce enough biomass to block light reaching the soil surface and modify soil temperatures. The seeds of some weed species need to be exposed to white sunlight to germinate, while many weeds are inhibited from germination by green light that has been filtered by plant leaves. Many weed seeds are sensitive to temperature, both absolute temperatures, i.e. they will not germinate if it is too cold, and also diurnal (day to night) temperature variation. Both of these are strong signals as to the time of year and therefore if conditions are good for growth or not. The thicker the residue, the lower the soil temperature and also the smaller the diurnal temperature variation so suppressing weed seeds germination. Likewise, the higher the biomass while the cover crop is still growing the lower the overall light levels and the more green light reaches the soil, further suppressing weed seed germination. Once terminated and browned off the green light effect is lost, however total light reaching the soil is still reduced.

Cereals typically produce the most biomass. For example, for the first two years of the five-year trial, oats produced the most biomass (Table 11). Only the first two years are presented due to poor establishment of the small-seeded clover and ryegrass in following years.

Table 11. Cover crop biomass in tonnes/ha dry matter at termination for the first two years of a trial of overwintered cover crops in maize at the FAR Northern Crop Research Site, Hamilton, from 2016 to 2021.

	Dry matter yield (t/ha)	
Cover crop	**2016**	**2017**
Clover	1.2	0.3
Bean	4.0	3.3
Oats	6.7	4.9
Ryegrass	4.6	2.3

A previous project looking at optimising maize and cover crop planting dates to maximise total biomass also found that annual cereals tended to yield the most (Figure 12). These results also highlight the considerable increase in biomass when cover crops are allowed to grow for as long as possible in spring. (Figure 12).

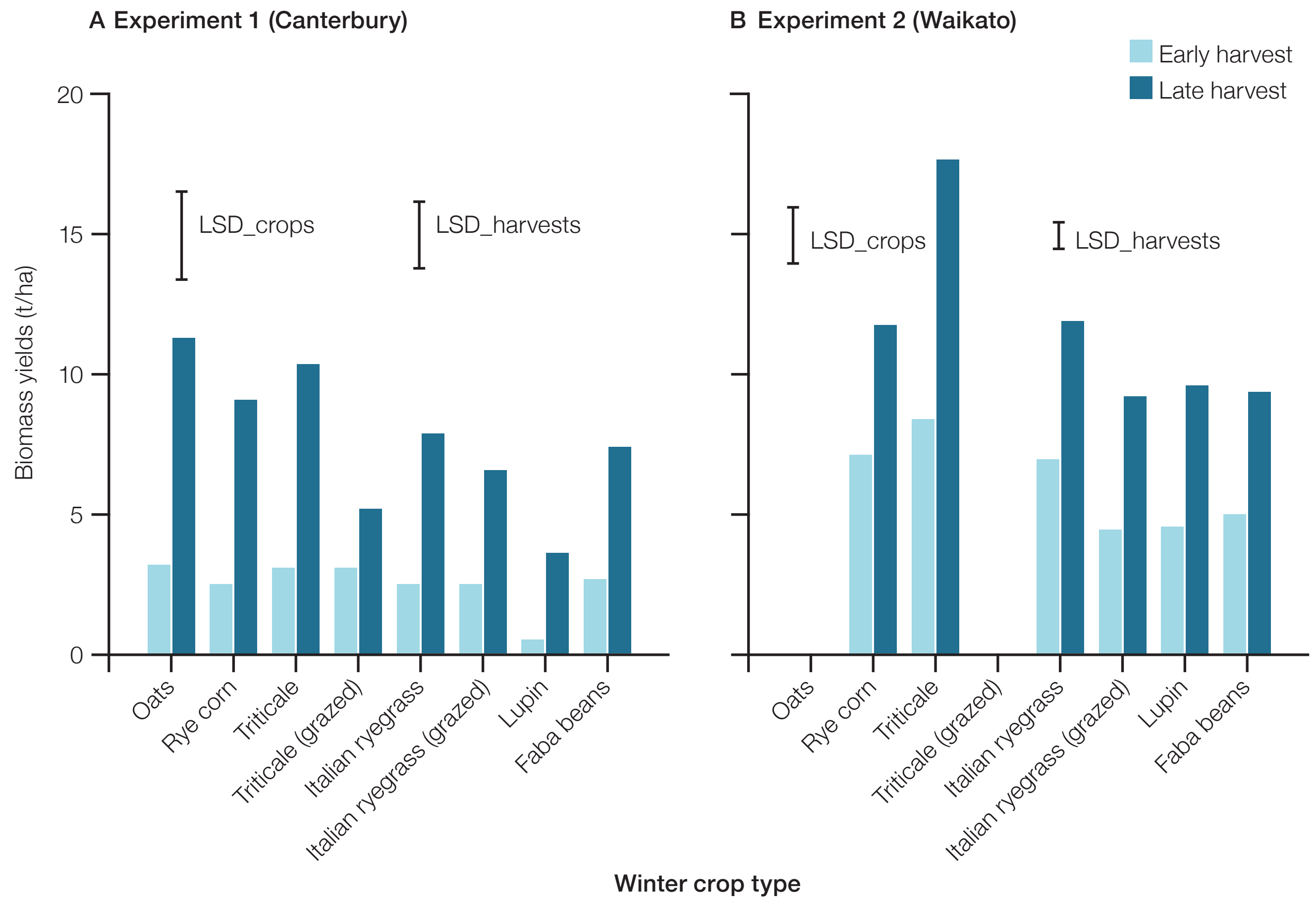

Figure 12. Dry matter yield (tonne DM/ha) for an early and late harvest of a range of winter cover crops grown in Canterbury and Waikato in 2009. The Canterbury cover crops were drilled on 5th May with early harvest cover crop grew for an average of 178 days (10th Oct) and the late harvest an average of 191 days (12th Nov). For Waikato, the cover crops were planted on 10th April, the early cover crop grew for an average of 213 days (9th Nov) and the late an average of 225 days (21st Nov).

Beyond the inherent biomass production potential of particular species and their cultivars, biomass can be increased significantly by increasing sowing rates. Most standard sowing rates, particularly for cereals, are based on the economics of seed production not biomass production. Increased sowing rates, up to double even treble standard rates, have been found to significantly increase biomass production. Where cover crops are being grazed, i.e. they are being grown as a fodder cash crop, achieving sufficient biomass is an important part of determining return on investment, while still providing sufficient soil cover over winter. The counterpoint to increased biomass and better weed suppression is the cost of the extra seed.

Biomass composition: carbon-to-nitrogen ratios

After the total amount of biomass produced by the cover crop, the next most important weed suppressing attribute is how long the dead residue persists for. This is primarily determined by the carbon-to-nitrogen ratio (C:N). Higher C:N ratios (a greater percentage of carbon) result in slower decomposition as the microbes don't have sufficient N (and other nutrients) to balance out the carbon through their metabolic processes. Lower C:N ratios results in faster decomposition.

Different plant groups produce residue with different C:N ratios. Cereals, especially when they are allowed to mature, have the highest C:N ratios and therefore decompose the slowest. Legumes, partly because they can fix atmospheric nitrogen, typically have the lowest C:N and thus decompose the fastest. Other species, e.g. brassicas like mustard and pasture grasses are intermediate between cereals and legumes. Where individual species cannot provide the desired C:N ratio, mixtures of species, e.g. a cereal and a legume, can give the required C:N ratio.

Cover crop sowing and termination dates

Maximising biomass is a key requirement for effective weed suppression, how long and when the cover crop is growing is an important determinant of final biomass and thus weed suppression. Clearly the longer a cover crop can grow, up to its point of maturity, the more biomass will be produced. Figure 13 shows the cumulative biomass production of a range of cover crop species grown over winter in five trials at FAR's Northern Crop Research Site between 2017 and 2022.

Clearly, the time of year that cover crops are grown will also impact biomass production. The periods of greatest growth are spring and into summer, and the lowest from autumn and through winter. For overwintered cover crops, the largest amount of biomass is often accumulated in the last few weeks in spring before termination.

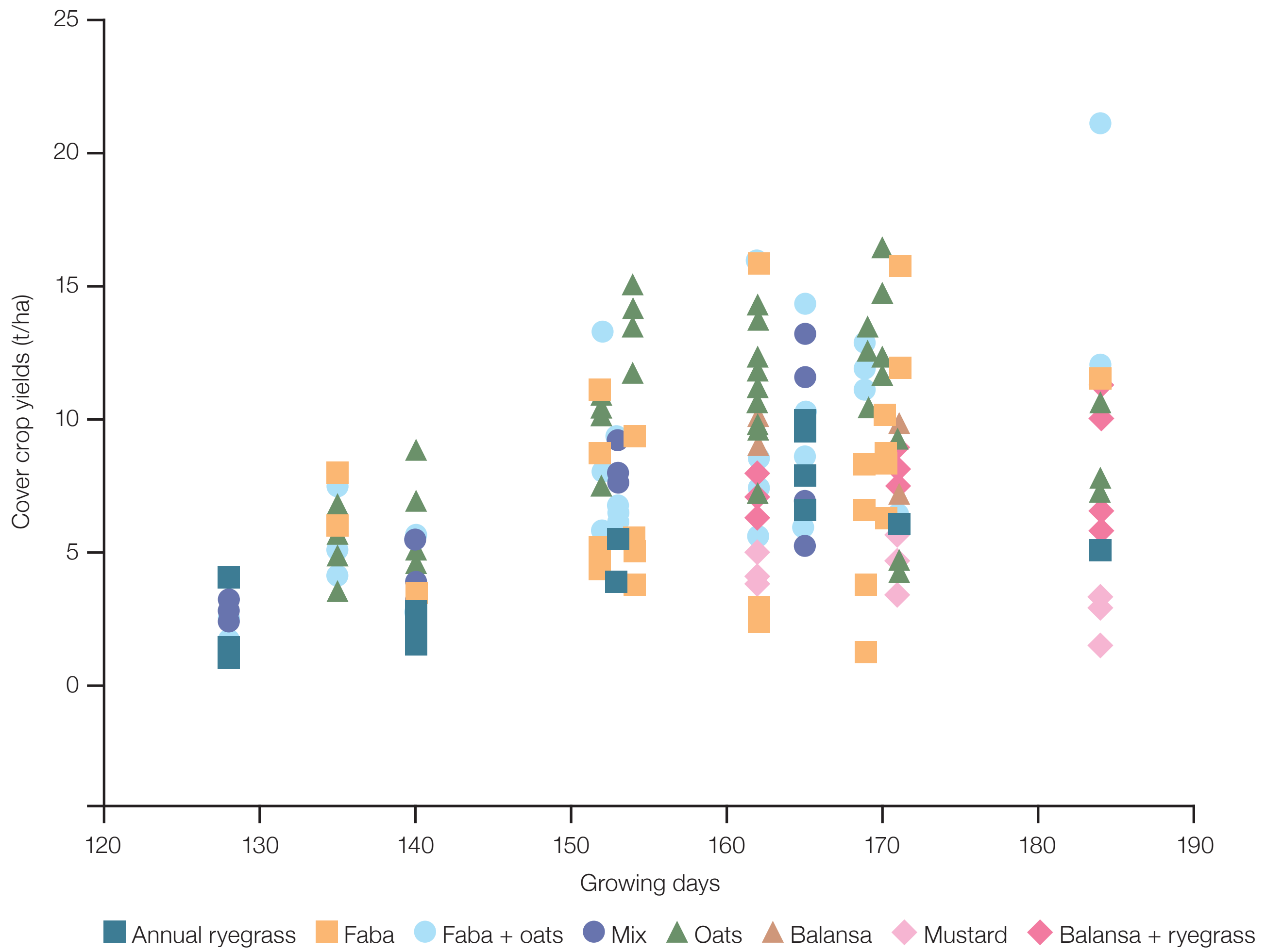

Figure 13. Winter crop biomass (yield, tonnes/ha) for different cover crop species with different growing days from five trials at FAR's Northern Crop Research Site between 2017 and 2022. From FAR internal report 'Review of cover crops in maize (X19-49)' A. Horrocks.

This was demonstrated in the five-year trial, when in the final year the cover crops were terminated in mid-October as opposed to previous years when they were terminated at the end of October / early November. The average dry matter yield for the first four years was 4.8 t/ha for beans and 6.1 t/ha for oats and 2.1 and 3.7 t/ha respectively for the final year. Beans and oats were the only cover crops grown in all five years that did not have establishment issues. Figure 12 shows the increase in biomass from allowing cover crops to grow as long as possible in spring.

The five-year trial highlights the trade-off between letting the cover crop grow for as long as possible (to maximise biomass production) and delaying the cash crop sowing (which may impact yield). The duration between cover crop termination and cash crop sowing also plays into overall timings.

Duration between cover crop termination and crop sowing

In the five-year trial the maize cash crop was sown within a few days of cover crop termination. This was partly due to the later sowing dates used in the first four years. Other FAR cover crop research has clearly shown a negative impact of sowing a cash crop directly after terminating the cover crop. Figure 14 shows the overall impact on a maize grain crop of a series of durations between terminating a range of different cover crops and planting maize, from 34 days between termination and planting and termination three days after planting. The crimper roller treatment was particularly low yielding; it failed to effectively kill the cover crops which then competed with the maize.

There are many reasons for cash crops being suppressed when sown after cover crop termination including:

- Reduced soil nitrogen and possibly other nutrients
- Reduced soil temperatures
- Reduced soil moisture
- Increased soil-borne diseases
- Allelopathic effects of cover crops

Cover crops take up plant available nutrients, particularly N. These are slowly released from the cover crop residues, both above and below ground, as they decompose, making them initially unavailable to the cash crop. To help compensate for reduced plant available nutrients, additional fertiliser can be applied at planting (best applied in-furrow), but results are not guaranteed. A number of trials by FAR and others have found that fertiliser applied at planting, even in-furrow, does not compensate when cover crops are terminated less than three weeks before maize planting, resulting in poor emergence and early growth. This suggests that other factors are impacting maize establishment; soil temperature is considered a likely cause.

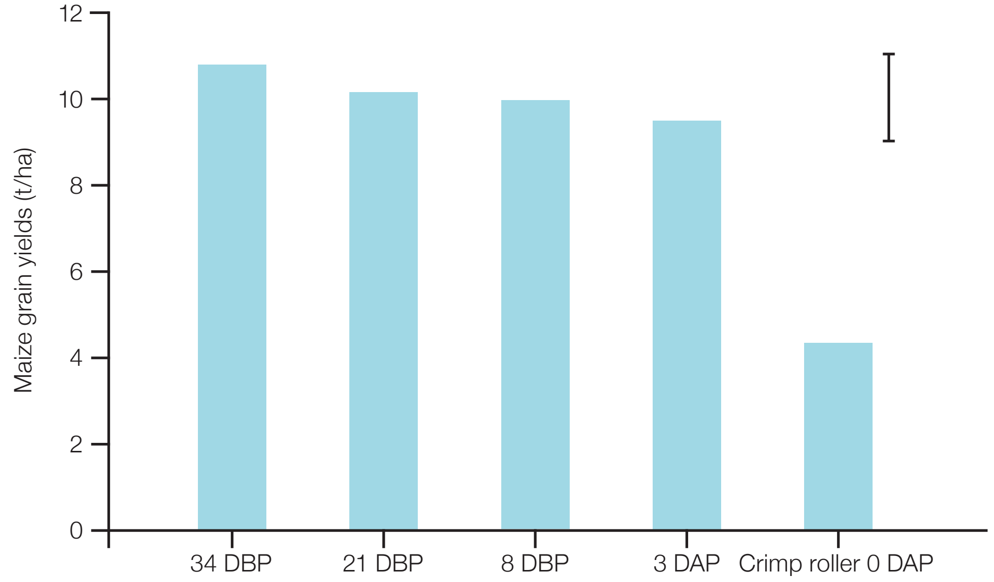

Figure 14. Maize grain yields (tonnes/ha) for durations between cover crop termination and maize planting of 34 to 8 days before planting (DBP), 3 days after planting (DAP) and roller crimping on the same day as planting, at the FAR Northern Crop Research Site, Hamilton in 2018. Error bar represents the LSD (5%). From FAR internal report 'Review of cover crops in maize (X19-49)' A. Horrocks.

Cover crop and any cash crop residue will reduce soil temperatures through shading and insulation. As a C4 plant, maize needs warm soil and air temperatures, so cooler soil temperatures may be a key factor in slower emergence and poorer establishment.

Cover crops can both reduce and increase soil moisture. They reduce it through transpiration of soil moisture, but can also help to retain it through shading the soil surface from sun and wind. Thus, whether cover crops reduce or increase soil moisture is specific to the particular cover crop and the weather (amount of sun, wind and rain) when the cover crop is in the ground. Cover crops are also grown as cash crops, so, where crop diseases, particularly soil-borne, are an issue, choose cover crop species that are not hosts for the disease pathogens, i.e. avoid creating a green bridge.

A few cover crops, such as ryecorn and barley, release allelochemicals in the first one to two weeks after termination. This can have considerable negative impacts on cash crop seed germination and early growth. The level of allelopathy among cultivars of allelopathic crops can vary, but no ryegrass allelopathy against maize has been identified. As microbes decompose residues, including plant roots, they release a wide range of biochemicals and gases (such as carbon dioxide) which can also negatively affect the cash crop; so negative effects of planting directly after a cover crop may not be due to allelopathy.

In the five-year trial, row cleaners were used to move the recently killed residue out of the crop rows. This may have reduced the impact of decomposition on the maize establishing directly after terminating the cover crop, but it is unlikely to have completely eliminated all cover crop impacts.

Surface applied nutrients, particularly nitrate, can stimulate weed seed germination allowing small, shallow rooted weed seedlings to access the nutrients before the crop. For this reason, fertilisers applied at, or soon after, planting are better applied down the spout, drilled in, or at least banded.

Allelopathy

Allelopathy is defined as plant-to-plant interactions mediated by biological chemicals (biochemicals), i.e. excluding competition for light, nutrients and water. While allelopathy is commonly considered to be a negative interaction, i.e. one plant suppressing another, it can be both negative and positive. Mostly, the biochemical interactions in the soil but they can also occur in the air via volatile biochemicals.

Allelopathy is often suggested to explain why some cover crops are particularly effective at suppressing other plants, both cash crops and weeds. However, proving that it is occurring is difficult, and what is thought to be allelopathic is actually linked to competition for light, nutrients and water. The impacts of allelopathy can also vary in strength due to factors such as crop species, cultivars, soil and weather.

However, it is a known issue, particularly in the first week or few after a cover crop is terminated, when allelochemicals leaching from the decaying crop residues can strongly negatively impact cash crops planted into fresh residues. Ryecorn, triticale and barley, in descending order, are known to be allelopathic, so care should be exercised when using them.

Non-weed effects of cover crops

As discussed in the introduction, unlike agrichemicals that have just one job, i.e. killing weeds, cover crops can have multiple effects. One of the more important effects is nitrogen fixation by leguminous cover crops, which often increases the amount of plant available N to the following crop. This contrasts with grasses, which with their fine fibrous root systems, are particularly good at taking up soil N, potentially resulting in insufficient N or even N deficiency in the following crop. Therefore, where leguminous and non-leguminous cover crops are being compared for their weed suppressing abilities, the impact of the cover crops on cash crop yield will be a function of both weed suppression and extra nitrogen availability following the legumes. This combined effect is difficult to disentangle without complex experimental designs. However, while the relative contribution to final yield from weed suppression and N fixation cannot be easily separated, at the paddock level it is the overall benefits of the cover crop on cash crop performance that is the main outcome of interest. This is clearly seen in the five-year cover crop trial where the legume cover crops resulted in the best maize yields even though they were not the best at weed suppression.

6.2.4 Main lessons from the five-year winter cover crop and herbicide trial

The trial analysed the effects of cover crops and herbicides separately and in combination.

6.2.4.1 Residue accumulation - problems and benefits

An unexpected challenge of the trial was the build-up of the maize stover residue over time to the point where it started affecting the establishment of the small seeded ryegrass and clover. This was initially addressed by cultivating the ryegrass and clover plots in 2018 after their establishment failed, which achieved a good strike and biomass (Figure 15).

To avoid having to cultivate these plots in future years the clover was replaced with vetch, and the ryegrass with a lupin and mustard mixture, in the final year.

It was noted in the later years of the trial that most of the weeds were establishing in the crop rows where the row cleaners on the maize drill had moved the maize residue aside from the row. Thus, in later years the maize residue was effectively acting the same as the cover crop residues and suppressing weeds. This may be an important benefit in continual no-till maize. However, how much of a role the maize residue is playing in weed suppression compared with the cover crop mulch cannot be determined in this trial as there were no treatments focused on that issue. These results are also at odds with general experience of no-till systems where grasses and small seeded broadleaf weeds have higher populations than larger seeded broadleaf weeds.

6.2.4.2 Cover crops achieved good weed suppression in the absence of herbicides

In the absence of herbicides, the cover crops achieved good levels of weed suppression. Figure 16 shows the average number of weeds per square metre for the cover crops and fallow around a month after maize planting. This shows that in most cases the cover crops caused a considerable reduction in weed populations compared with the fallow. The exception is the final year, when maize was sown earlier and cover crops did not achieve the same amount of biomass. In the first year weeds were low overall as the trial area had been in pasture prior to the trial establishment.

While weed populations are a valuable measure, lots of small weeds may not be as problematic as a small number of larger ones. While weeds that have emerged at establishment are responsible for most yield losses, weeds that survive into later crop stages can still compete with the crop and may set seed, increasing the size of the weed seedbank. For this reason, weed ground cover at canopy closure was also measured. Figure 17 shows the percentage of ground covered by weeds in the fallow and cover crop treatments in the absence of herbicides.

The increasing weed cover in the clover and ryegrass in Figure 17 in the 2017-18 and 2018-19 seasons is most likely the result of the poorer establishment of these cover crops resulting in decreasing cover crop biomass (Figure 15) resulting in lower weed competition.

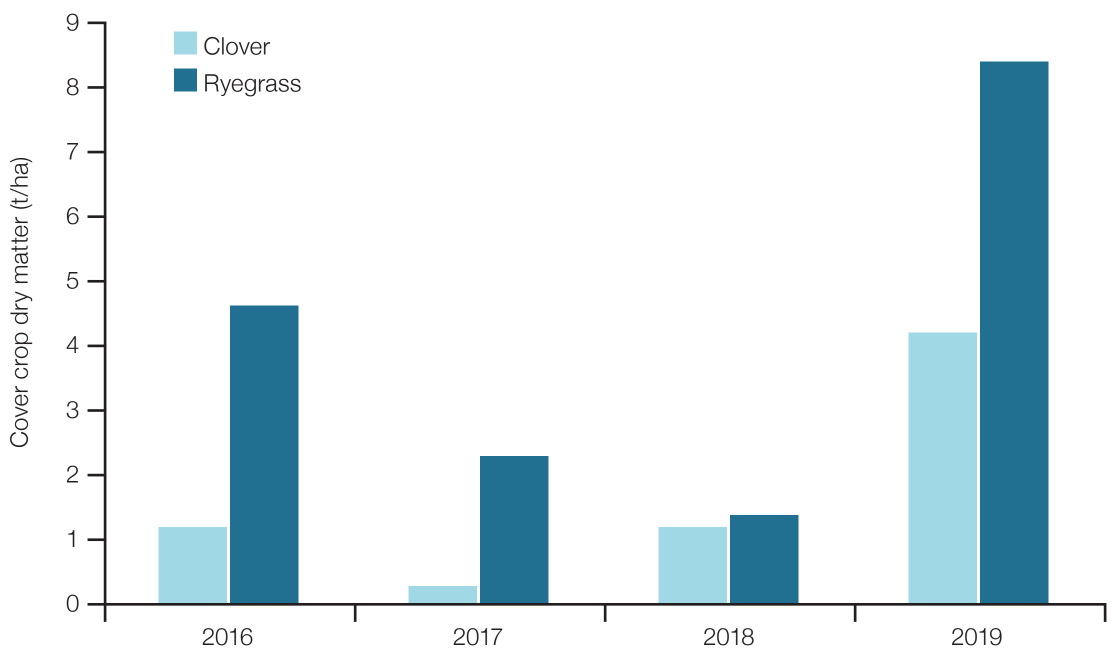

Figure 15. The decline in cover crop biomass (dry matter tonne/ha) of clover and ryegrass between 2016 to 2018 due to residue build-up, and the yield recovery when residue was cultivated prior to sowing in 2019, in a trial of overwintered cover crops in maize at the FAR Northern Crop Research Site, Hamilton, from 2016 to 2021.

In comparison to the clover and ryegrass, the beans and oats successfully established in all years and reduced weed ground cover in the absence of herbicides to about half of that of the fallow in the same year and, on average, across all four years (Figure 17).

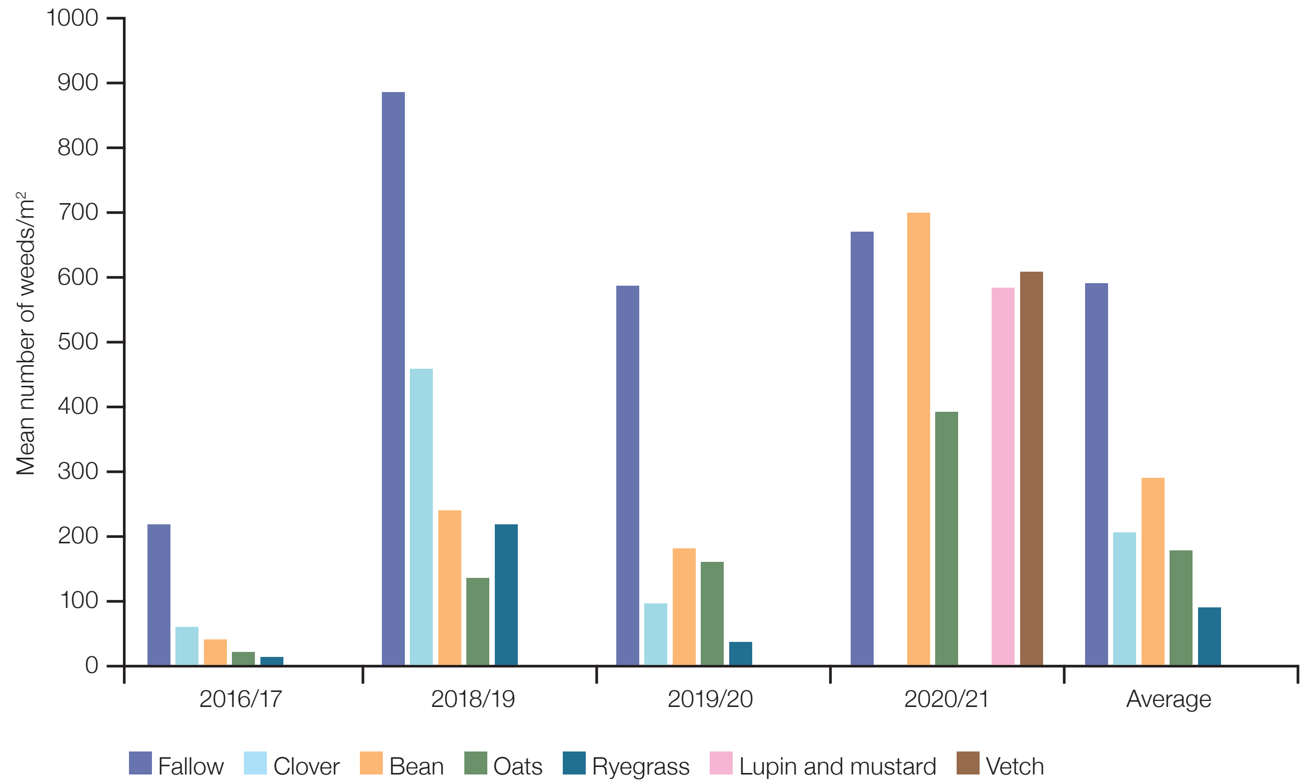

Figure 16. The average number of weeds/m^2 for the different cover crops in the non-herbicide plots, over four seasons, three to five weeks after maize emergence, in a trial of overwintered cover crops in maize at the FAR Northern Crop Research Site, Hamilton, from 2016 to 2021.

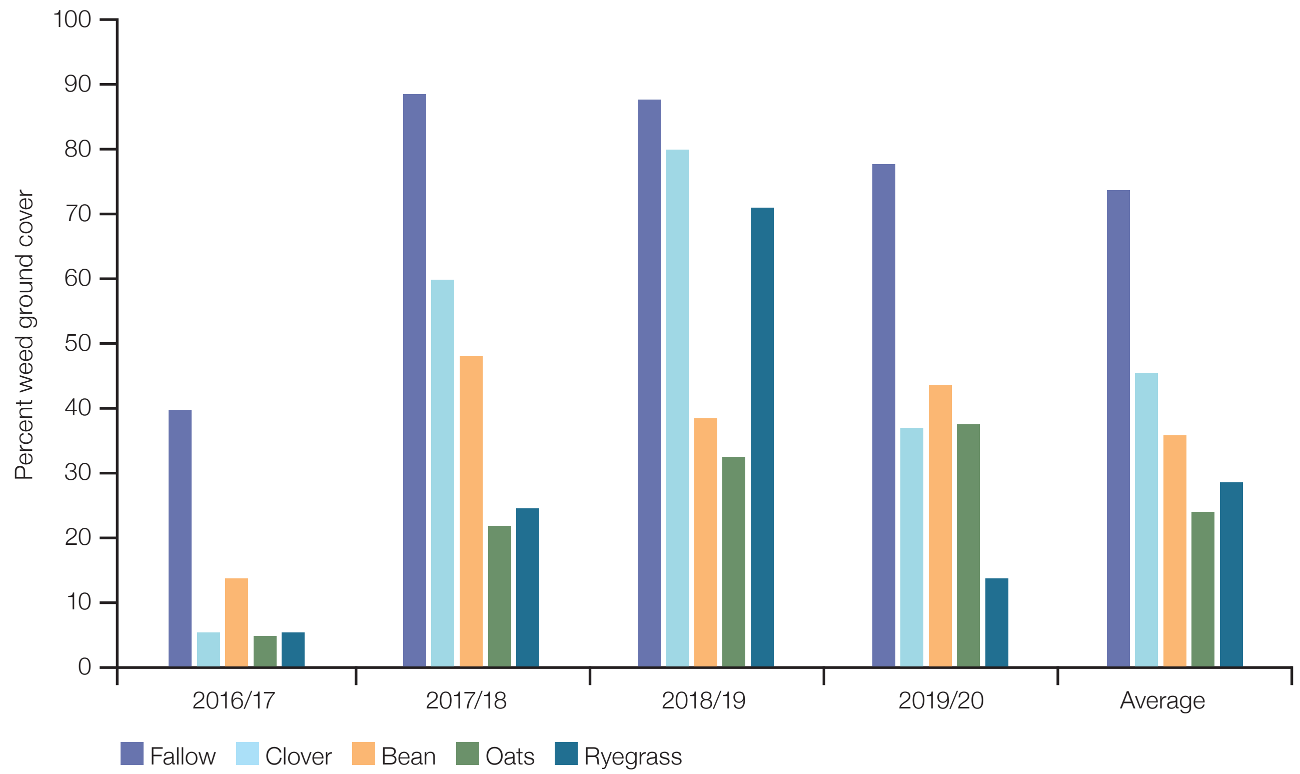

Figure 17. The percent weed ground cover at maize canopy closure of the cover crops and bare fallow in the absence of herbicide, in a trial of overwintered cover crops in maize at the FAR Northern Crop Research Site, Hamilton, from 2016 to 2021.

6.2.4.3 Maize and cover crop sowing dates

The lower weed suppression in the final year is most likely due to the earlier maize sowing date (less time for the cover crops to grow sufficient biomass in the spring). As this date is more aligned with typical sowing dates, it indicates that cover crops would be less effective than indicated by results in the earlier years of the trial. The trial was also direct drilled (no-till) while most ground for maize is cultivated. Cultivation increases soil temperature due to destruction of surface residue allowing the sun to directly heat the soil and also allowing greater air movement through the soil's surface layers. Conversely having cover crop residue on the soil surface and direct drilling will result in cooler soil temperatures. As maize needs warmer soil temperatures for germination and growth, delaying sowing may be important in direct-drilled cover crop systems to allow the soil to warm up sufficiently. This will make harvest dates later and is likely to impact yield. Another factor to consider is that the trial was a grain crop, so harvested considerably later than maize silage. The earlier harvest date of silage would allow cover crops to be planted earlier when the weather is warmer. This would allow them to grow considerably more biomass before slowing down over winter. Cover crops could be considerably more effective in silage than grain crops.

One option to achieve sufficient cover crop growth and biomass production while maintaining standard planting dates for maize grain crops could be to 'relay-plant' the cover crops into the maize i.e. planting into the previous crop while it is still growing. Both crops can be cash or cover crops, and typically the following crop is planted between the rows of the first (or broadcast in the case of undersowing). The overlap where both crops are in the ground simultaneously, 'passing the relay baton', can vary greatly. The 'following' crop may be sown into the preceding one not long after establishment, or as little as a few weeks before the end of the preceding crop's life. The latter is also often called "undersowing". The FAR research into cover crops to mitigate overwinter nitrate leaching uses relay cropping.

A specific form of relay cropping gaining interest is "planting green". This is where a cash crop is planted into the preceding cover crop while the cover crop is still green, the cover crop is then terminated before the cash crop emerges. The cover crop is typically terminated with glyphosate (Group 9) applied in the period shortly before drilling the cash crop to shortly after drilling (but always before the cash crop emerges). Crimper rollers can also be used to terminate the cover crop before the cash crop emerges.

Both relay cropping and planting green are highly advanced techniques that should only be attempted by experienced cover croppers and no-till / direct-drill growers, and trialled on small areas which can be written off if the process fails.

6.2.4.4 The impact of herbicides in the absence of cover crops on weeds

As the main focus of the five-year trial was on the use of cover crops, less data was collected on herbicide performance in the absence of cover crops, i.e. in the fallow plots. Table 12 shows the average percentage weed cover in fallow plots (no herbicides, no cover crops) at maize canopy closure compared with the herbicide treatments in the absence of cover crops. This clearly demonstrates that all herbicides reduced weed cover to very low levels.

While all herbicides significantly reduced weed cover, the differences among the herbicides were mostly small. The combination of a pre- and post-crop emergence herbicide completely eliminated all weed cover in all years. The single pre-emergence herbicide application was the least effective in two years but achieved complete control in a third (Table 12). The pre-emergence herbicide acetochlor (Group 15) needs a residue free seedbed and 10 to 30 mm of rain or irrigation post-application to move it sufficiently into the soil surface. Its efficacy may have thus been reduced if the row cleaners on the drill failed to completely move residue away from the drill furrow, and/or there was insufficient soil moisture. This may explain the year to year variation. All herbicide treatments where a post-emergent herbicide was used were effective at controlling weeds, although slightly less so in the 2020-21 season when residuals were more effective (Table 12). There was no benefit of applying two post-emergence herbicides compared with just one post-emergence application, however, the data cannot determine if this is just an effect of timing or of the herbicides used. Both Treatment 3 (pre- and post-emergence at five weeks after emergence) and Treatment 4 (post-emergence at three weeks after emergence) used topramezone (Group 27) + atrazine (Group 5), while Treatment 5 (early and late post-emergence) used mesotrione (Group 27) and atrazine at two weeks and nicosulfuron (Group 2) at five weeks.

Table 12. Average percentage weed cover in fallow (bare) plots at maize canopy closure, in a trial of overwintered cover crops in maize at the FAR Northern Crop Research Site, Hamilton, from 2016 to 2021. Pre-emergence = acetochlor Group 15 + saflufenacil Group 14, 1.3-0 weeks before maize emergence (WBE). Pre+post-emergence = acetochlor + saflufenacil 1.3-0 WBE and topramezone Group 27 + atrazine Group 5, 5.1-5.7 weeks after maize emergence (WAE). Post-emergence = topramezone + atrazine 5.1-5.7 WAE. Two post-emergence = mesotrione Group 27 + atrazine 1.9-2.6 WAE and nicosulfuron Group 2 5.1-5.7 WAE.

Treatment	2017-18	2018-19	2020-21	Average
1. No herbicide	88.3%	87.3%	48.8%	74.8%
2. Pre-emergence herbicide	3.5%	7.6%	0.0%	3.7%
3. Pre- and post-emergence herbicide	0.0%	0.0%	0.0%	0.0%
4. Single post-emergence herbicide	0.4%	0.9%	3.0%	1.4%
5. Early and a late post-emergence herbicide	0.9%	0.7%	3.3%	1.6%

The reduction in weed ground cover achieved by herbicides without cover crops is significantly greater than that achieved by cover crops without herbicides which overall achieved approximately a 50% reduction in weed cover (Figure 17).

6.2.4.5 Combined impacts of cover crops and herbicides on weeds

While in-crop weed management is important for getting the crop through to harvest and a good yield, in integrated weed management in annual cropping systems it is the size and diversity of the weed seedbank that is the fundamental measure of the overall success of a weed management system. The weed seedbank was therefore measured at the end of the trial. Two comparisons were made, one compared the different cover crops and fallow with and without herbicides (Figure 18), the second compared the five different herbicide treatments when used with a cover crop or in the bare fallow (Figure 19).

Where cover crops were grown without herbicides, ryegrass and clover were the most effective at minimising the weed seedbank, faba bean was intermediate and oats were no different to the fallow (Figure 18). It is unclear why oats should have the largest weed seedbank as they were among the best at suppressing weeds up to canopy closure. Where herbicides were used with the cover crops the additional weed control has a clear impact on the weed seedbank, resulting in an average reduction of about two thirds, with bigger reductions in the oats and beans that were less effective at reducing the seedbank by themselves (Figure 18).

Where cover crops were used in the absence of herbicides there was about a one third reduction in the weed seedbank compared to the null control (fallow), but, the seedbank was still considerable at nearly 600 seeds (Figure 19), though the large difference among the cover crops shown in Figure 18 needs to be taken into consideration.

Reflecting the levels of weed ground cover at crop canopy closure (Table 12), herbicides alone achieved reductions in the weed seedbank of about half to a quarter (Figure 19). This indicates that the pattern of weed management at the start of the crop followed through to weed seed rain and the weed seedbank. Cover crops improved the effects of the herbicides by further decreasing the size of the seedbank with larger reductions where herbicides were less effective by themselves (Figure 19). The biggest reduction was in the pre-emergence only herbicide, which had the largest seedbank of all the herbicides (about half that of the fallow). This indicates that the cover crops were doing a larger share of weed management when herbicide efficacy was lower (Figure 19). These results also show that the pre-emergence herbicide by itself was not as effective as post-emergence herbicides, but that using both a pre- and post-emergence herbicide, or having two post-emergence applications were just as effective as the single post-emergence treatment, as also show in Table 12.

These results reinforce the other weed management results, showing that the cover crops achieved good amounts of weed suppression and that when cover crops were combined with a single post-emergence herbicide application weed control was as good as two herbicide applications. As the number of herbicide applications is a key driver of herbicide resistance, using only one post-emergence application in maize is really valuable.

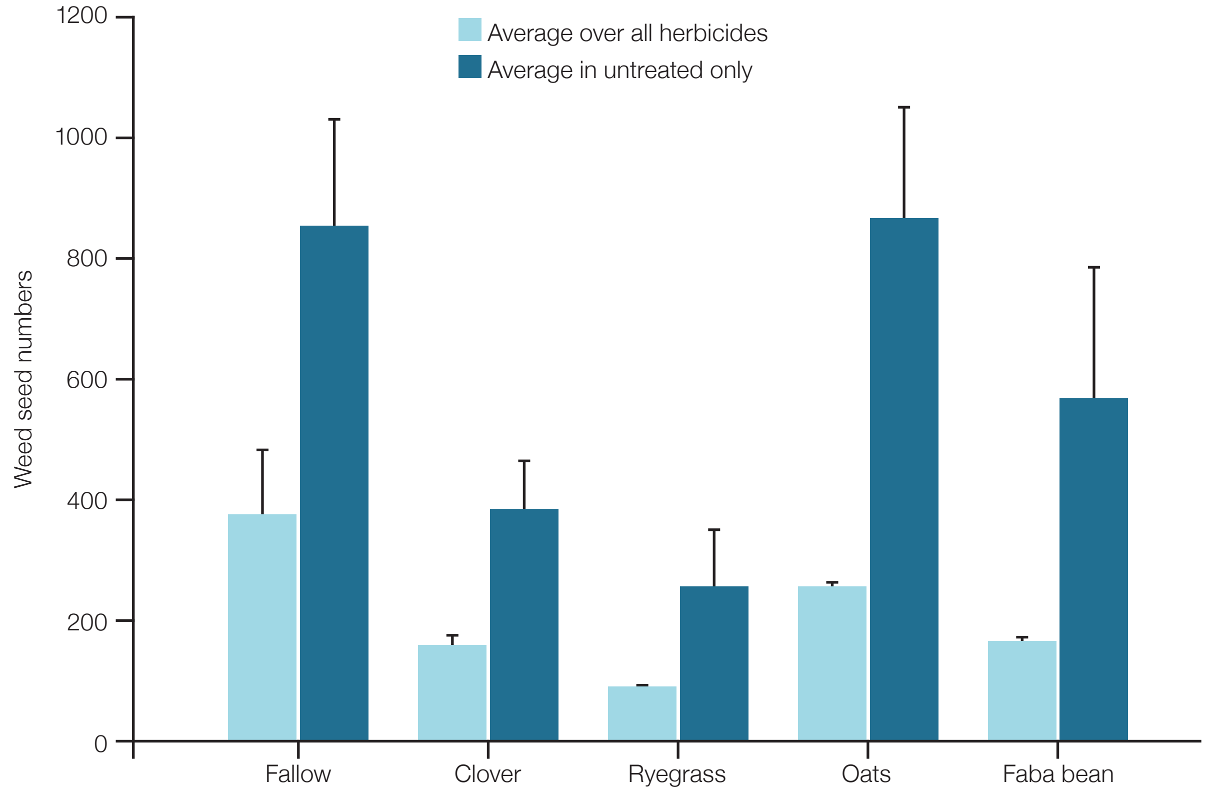

Figure 18. Comparison of average weed seedbank in a 500 g soil sample under cover crops and fallow with pooled herbicide treatments and in the no herbicide control, in a trial of overwintered cover crops in maize at the FAR Northern Crop Research Site, Hamilton, from 2016 to 2021. Error bars are the SEM for each data set.

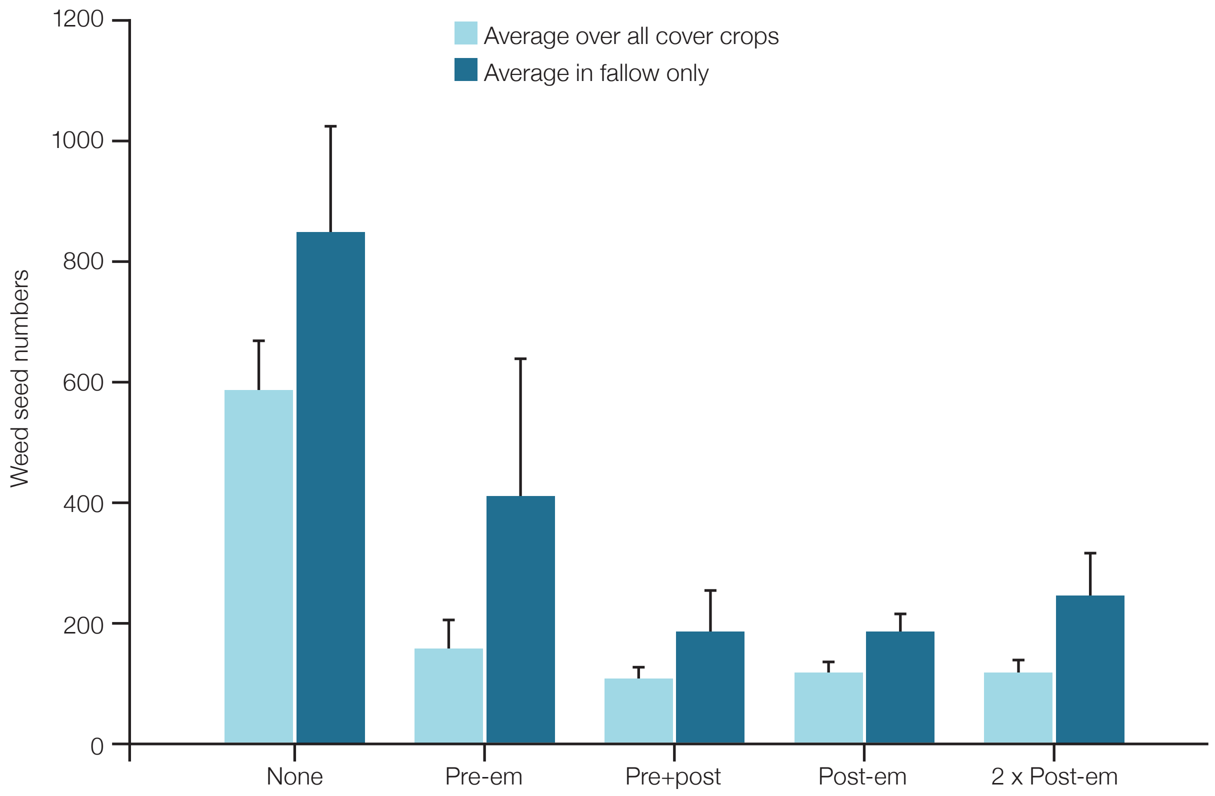

Figure 19. Comparison of average weed seed bank in 500 g of soil under four herbicide treatments with pooled cover crops and under the no cover crop fallow, in a trial of overwintered cover crops in maize at the FAR Northern Crop Research Site, Hamilton, from 2016 to 2021. Pre-emergence = acetochlor Group 15 + saflufenacil Group 14, 1.3-0 weeks before maize emergence (WBE). Pre+post-emergence = acetochlor + saflufenacil 1.3-0 WBE and topramezone Group 27 + atrazine Group 5, 5.1-5.7 weeks after maize emergence (WAE). Post-emergence = topramezone + atrazine 5.1-5.7 WAE. Two post-emergence = mesotrione Group 27 + atrazine 1.9-2.6 WAE and nicosulfuron Group 2 5.1-5.7 WAE. Error bars are the SEM for each data set.

6.2.4.6 Impacts of cover crops and herbicides on maize yield

Maize grain yield was measured by manually harvesting cobs from six metres of row in early May, except for 2021 which was harvested mid-April due to the earlier sowing date. There was no harvest in 2020 due to COVID-19 lockdown restrictions.

As discussed above, cover crops have multiple effects. A key secondary effect to weed management in this trial was that the legume cover crops fixed atmospheric nitrogen (N) and thus increased soil N levels. This is the most likely reason for the maize following legumes having the highest yields, even though they had the lowest weed suppression. The grass cover crops may also have been tying up some soil N compared with the fallow, which may have slowed down maize growth. While scientifically it would be valuable to separate out the nutrient and weed suppression effects, that is not possible with this trial design, and at the paddock level the key outcome is what was the overall impact of cover crops on yield.

Figure 20 shows the effects of cover crops and herbicides on the average maize grain yield across all four harvests for the fallow, then cover crops and herbicides individually, and the combined effects of cover crops and herbicides. The full null control of fallow (no cover crops) and no herbicides had the lowest yield. Cover crops alone caused a significant yield increase of 1.3 t/ha. Fallow with herbicides slightly increased yield over cover crops at 0.4 t/ha. Finally, combining cover crops and herbicides gave another increase but it is the smallest increase of just 0.1/ha (Figure 20).

Figure 21 shows that across the herbicide trials, yield was lowest in the no-herbicide treatments followed by the pre-emergent only treatment However, based on each year's data analysis, the differences were mostly not statistically significant. The slightly lower yield does however match up with the higher levels of weeds in the non-herbicide and pre-emergence only treatments.

Figure 22 shows the effect of cover crop and fallow on maize grain yield. The two legumes, clover and bean, have a slightly better yield than the fallow, and the two grasses oats and ryegrass were the same or slightly lower than the fallow, though the difference was only statistically significant in some years. However, care is required in interpreting these results due to the impact of the increasing amount of maize residue on the small seeded ryegrass and clover reducing their biomass. The lupin plus mustard and vetch treatments which were only grown for the final year, produced a slightly above average yield for all cover crops; this may have boosted maize yield, so they cannot be directly compared with the other cover crops.

Table 13 shows the maize grain harvest for all four harvests by both cover crop and herbicide treatments. The nitrogen fixing clover and faba bean achieve a significant increase in maize grain yield over fallow, but combining them with herbicides created no or limited yield increase except for the double post-emergent herbicide treatment. In comparison, the oats only had a small maize yield increase over fallow while ryegrass has a small decrease. Combining with herbicides also had limited or no benefit (Table 13). All the herbicide treatments increased yield over fallow, but, not as much as when combined with clover and beans. In comparison, combining herbicides with oats had no or small yield benefits. The small yield reduction from ryegrass over fallow, was mostly maintained when combined with herbicides, as the combined yields were slightly lower than herbicides combined with fallow, except for the single post-emergent herbicide (Table 13). That the herbicides were not increasing maize yields when combined with the two grass cover crops indicates the yield decrease was unlikely due to weeds, but more likely due to soil effects, with nitrogen tie up the most likely cause. This is the opposite of the legumes, where nitrogen fixation is considered to be the most likely cause of the increased maize yield.

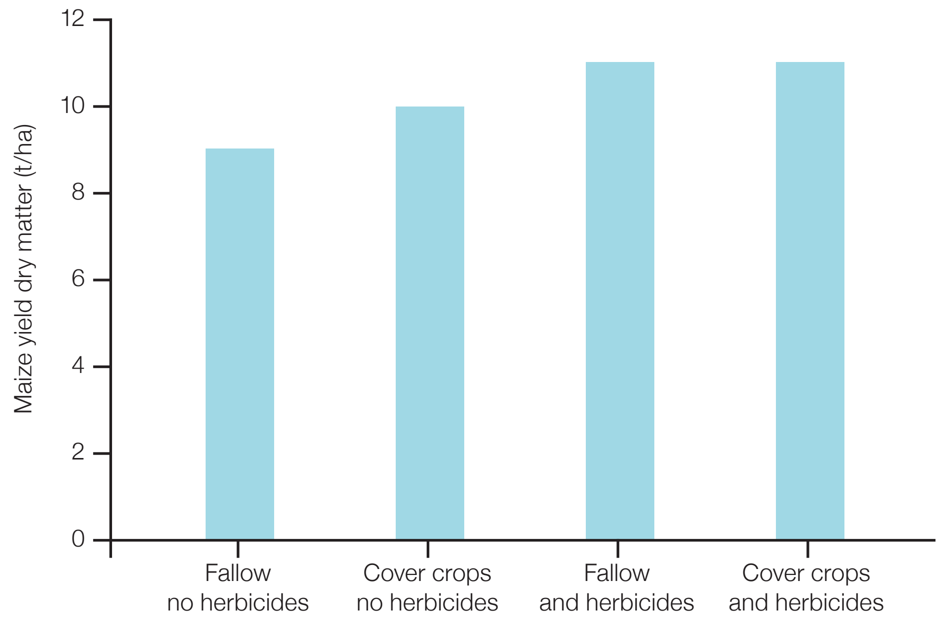

Figure 20. Overall impact of cover crops and herbicides on maize grain yield over four years, in a trial of overwintered cover crops in maize at the FAR Northern Crop Research Site, Hamilton, from 2016 to 2021. There were only four years data due to no harvest in 2020 due to COVID-19 lockdown restrictions.

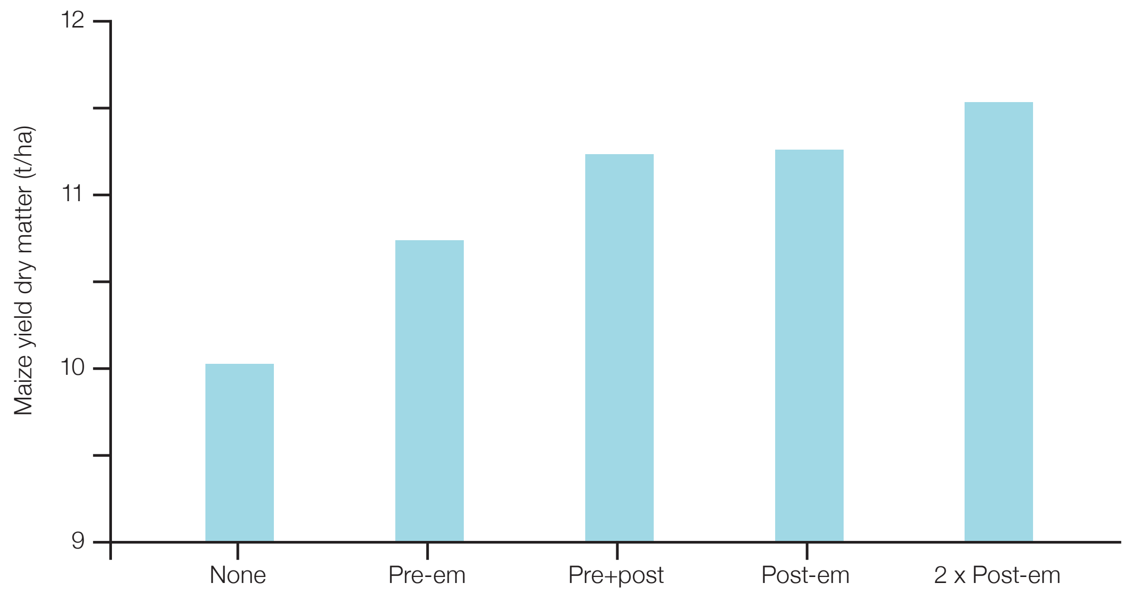

Figure 21. Average of four years maize grain yield in tonnes dry matter per hectare by herbicide treatment, in a trial of overwintered cover crops in maize at the FAR Northern Crop Research Site, Hamilton, from 2016 to 2021. Pre-emergence = acetochlor Group 15 + saflufenacil Group 14, 1.3-0 weeks before maize emergence (WBE). Pre+post-emergence = acetochlor + saflufenacil 1.3-0 WBE and topramezone Group 27 + atrazine Group 5, 5.1-5.7 weeks after maize emergence (WAE). Post-emergence = topramezone + atrazine 5.1-5.7 WAE. Two post-emergence = mesotrione Group 27 + atrazine 1.9-2.6 WAE and nicosulfuron Group 2 5.1-5.7 WAE.

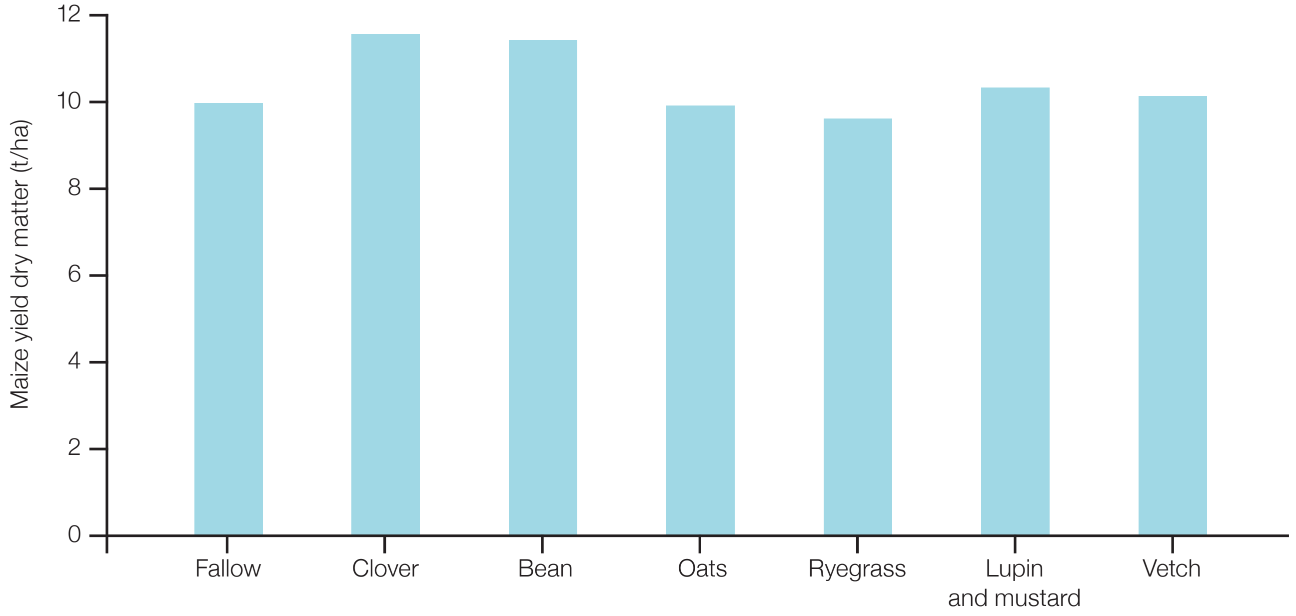

Figure 22. Average of four years maize grain yield in tonnes dry matter per hectare planted after six different cover crops and fallow, in a trial of overwintered cover crops in maize at the FAR Northern Crop Research Site, Hamilton, from 2016 to 2021. The lupin and mustard and vetch cover crops were only grown in the final year, which was above average, so should not be directly compared with the other cover crops. There were only four years data due to no harvest in 2020 due to COVID-19 lockdown restrictions.

Table 13. Average of four years maize grain yield in dry matter tonnes/ha by herbicide and cover crop, in a trial of overwintered cover crops in maize at the FAR Northern Crop Research Site, Hamilton, from 2016 to 2021. Pre-emergence = acetochlor Group 15 + saflufenacil Group 14, 1.3-0 weeks before maize emergence (WBE). Pre+post-emergence = acetochlor + saflufenacil 1.3-0 WBE and topramezone Group 27 + atrazine Group 5, 5.1-5.7 weeks after maize emergence (WAE). Post-emergence = topramezone + atrazine 5.1-5.7 WAE. Two post-emergence = mesotrione Group 27 + atrazine 1.9-2.6 WAE and nicosulfuron Group 2 5.1-5.7 WAE. There were only four years data due to no harvest in 2020 due to COVID-19 lockdown restrictions.

Treatment	Fallow	Clover	Bean	Oats	Ryegrass	Overall average
No herbicide	9.1	11.4	11.7	9.9	8.8	10.2
Pre-emergence herbicide	10.0	11.0	11.9	9.5	9.3	10.3
Pre- and post-emergence herbicide	11.1	11.3	12.3	10.5	9.6	11.0
Single post-emergence herbicide	10.3	11.7	11.7	10.0	10.7	10.9
Early and late post-emergence herbicide	11.9	12.6	12.2	10.2	9.7	11.3
Overall average	10.5	11.6	11.9	10.0	9.6	10.7

6.2.4.7 Five-year trial conclusions

This trial demonstrated that mulch from winter cover crops can be used in an integrated weed management approach in maize grain crops. Cover crops without herbicides can achieve good weed suppression, and, when combined with a single post-emergent herbicide, achieve effective weed management while maintaining silage and grain yields. Despite their slightly lower weed suppressive ability, legume-based cover crops resulted in slightly higher yields than grasses such as oats and annual ryegrass, potentially due biological nitrogen fixation by the legumes. With the exception of oats, all cover crops and all herbicide treatments reduced the weed seed banks compared with fallow and no herbicides respectively, showing that using cover crops will not result in longer term weed build-up.

These results refer to maize trials in a no-till system with retained residue and planted late. This contrasts with typical North Island maize crops, both grain and silage that are cultivated, often grazed post-harvest, and planted a month or so earlier. With the later harvest date of maize grain compared to silage crops, using over-wintered cover crops in silage crops should produce more biomass due to earlier planting and thus be more effective.

Further research is required to work out how to use cover crops for weed management in more typical production systems.

6.2.5 Cover crop conclusions

The results from this five-year trial, along with a range of other FAR research on cover crops, show they have an increasingly important role to play in maize. Benefits include:

- Improving overall soil quality which can increase yield in the longer term.
- Protecting soil from sun, wind and rain, particularly overwinter, as an alternative to bare fallow.
- Reducing overwinter nitrate leaching.
- Leguminous cover crops can fix sufficient amounts of atmospheric N to increase soil nitrogen enough to increase maize yields.
- Working with herbicides to achieve good weed management, and allowing a reduction in herbicide use to help reduce the risk of herbicide resistance.

CASE STUDY

6.2.6 No-till and cover crops

Chris Pellow

Chris farms at Onewhero, northern Waikato. His total cropping area is 120 hectares in three blocks. He grows 110 ha of maize grain and silage and 10 ha for barley. There are no livestock on the farm.

Maximising "living root days", planting green and retaining soil organic matter through the use of no-till and cover crops has the added benefit of suppressing weeds on Chris Pellow's farm.

Chris introduced no-till into his maize production system in 2001 and by 2005 was using it to establish all crops, other than when contouring land for surface drainage. The home block and a lease block are clay loam and clay, more difficult soil types for practicing no till, which has been a learning curve.

Most of the maize grown is for grain. About 10 ha of barley is grown where fields need to be contoured, providing a small area of rotation away from maize. Previously, oats were grown and baled following maize silage but interest in round baled oat silage was unpredictable. After trialling cover crops, Chris switched completely to these after quitting oats in 2016. Initially he used a lot of brassicas, mainly mustard, but has also grown tillage radish, phacelia and buckwheat. Legumes grown are faba beans, lupins, vetch, peas and clover. Cover crops are direct drilled after the maize is harvested and left to grow without added fertiliser until spring. These have improved soil structure and health and are building organic matter.

As there is no livestock grazing or silage/hay made, Chris doesn't get any direct income from cover crops but says they contribute to considerable saving on inputs for the next crop through nitrogen and other nutrient savings and not having to use insecticide seed treatments.

In terms of tips for establishing cover crops after maize, the earlier they are planted the better, he says. "As with any winter crop, getting good seed to soil contact through the residue is critical, especially for crops with larger sized seed." It can be difficult to establish cover crops later in the season and in damp soil conditions.

No grass cover crop species are used as it is too hard to get good maize crop establishment under no-till, Chris says. Grass needs to be sprayed six to eight weeks before planting to allow the root structure to break down to allow good seed slot closure. Not using grasses also eliminates the need to use insecticide seed treatments.

Prior to planting maize, Chris crimp rolls the cover crop, forming a thatch or mulch that helps to suppress weeds and early weed growth. "The aim is to keep living roots in the soil as close to 365 days a year as I can." Rolling and planting is done within a day or two, with the mulch left by the cover crop not hindering maize emergence. "Rolling is more to enable accurate broadcasting of fertiliser and to provide a better mulch as the planter can handle going into a full cover crop." Generally, glyphosate is applied post-planting to clean up any cover crop that hasn't died with the crimp rolling, as well as any weeds. The main weeds tend to be grasses, with weeds gradually declining over time, despite continuous cropping of maize.

"No-till has changed the weed spectrum to more shallow-rooted weeds, so more grasses and less issues with deeper rooted weeds like dock, as you are not burying seed and mixing it through the soil profile." Pre- and post-emergence herbicide is used as required, but usage is reducing because of the cover crops. "If I can grow a good heavy cover crop, I can eliminate the pre-emergence herbicide."

Having legume cover crops has also led to savings of up to 160 kg/ha in applied nitrogen. With the cover crops, Chris has largely settled on a legume mix of faba beans and lupins, but is also trialling a permanent crop of clover for year-round cover. While many growers use annual clover as a cover crop, management of perennial clover is less well understood. "You've got to knock it back each year to get the maize established, generally with glyphosate around planting."

Chris is an early pioneer of precision agriculture in maize and has been yield mapping since 2009. He operates row control and variable rate seeding on the planter, section control and variable rate application on the fertiliser spreader and side-dresser and section control on the sprayer. Grid soil sampling is used to match inputs to soil productivity capacity. Deep-N testing (mineral N test), at a depth of 600 mm, and variable rate N application started in 2014.

6.2.7 Further cover crop resources

There are a wide range of resources on cover cropping in general and weed management specifically. The following are some key cover cropping information sources. There are also a large amount of information on the internet, particularly from the United States, and increasingly from Europe.

- An introduction to the principles of service (cover) crops and intercropping www.bhu.org.nz/future-farming-centre/information/bulletin/2023-v3/an-introduction-to-the-principles-of-service-cover-crops-and-intercropping/
- Managing cover crops profitably 3rd ed 2007 SARE www.sare.org/resources/managing-cover-crops-profitably-3rd-edition/
- SARE Cover Crops www.sare.org/sare-category/crop-production/cropping-systems/cover-crops/
- SARE Cover crop innovators video series. www.sare.org/What-We-Do/Impacts-from-the-Field/Cover-Crop-Innovators-Video-Series/
- Agricology agricology.co.uk/resource/cover-crops/
- Organic Farm Knowledge Cover crop and living mulch toolbox organic-farmknowledge.org/tool/30563#!
- Green Manuring Principles and Practice 1927 Pieters soilandhealth.org/book/green-manuring-principles-and-practice/

Links to multiple cover crop resources. SoilCare. www.soilcare-project.eu/soil-improving-cropping-systems/soil-improving-crops/20-cropping-systems/142-cover-crops

6.3 Field margin and fence-line management

See Section 3.3 'Fence-lines and other uncropped areas under the herbicide resistance section for fence-line management information.

6.4 Cultivar and crop establishment

Getting the crop off to the best possible start is critical to a good crop and effective weed management. All the usual advice applies, use high health seed with good vigour, ensure soil and weather conditions (tilth, temperature, moisture, etc.) are conducive to good establishment, and poor conditions are avoided where possible.

Internationally, new maize hybrids, changed establishment patterns e.g. narrow rows, and banding fertiliser have improved maize competition with weeds and significantly increased yields. For example, a review paper found that narrowing row spacing to half the standard distance reduced weed biomass by 39 - 68%, and increasing maize planting density by up to twice the standard rate achieved a reduction in weed biomass of 26 - 99%. Hybrids with high leaf area index, and other elements of leaf architecture that improve light interception by the crop increase shading of weeds. There are also combined effects where one technique, e.g. narrow rows, is further increased by another, e.g. fertiliser banding. To date there is no New Zealand research looking at the impact of hybrids on weed management. There is work looking at row spacing on yield.

6.5 Managing weed seedbanks

Key points:

- The weed seedbank is the heart of the annual weed problem in arable cropping systems.
- Minimising weed seed rain and thus the replenishment of the weed seedbank is a key focus of integrated weed management.
- Seed banks can decline significantly in just a few years if there is a deliberate strategy to stop annual weeds from setting and dropping seed, i.e. the weed seed rain.
- Weed seed survival depends on the type of seed coat, depth of burial and the soil environment. Most grass weed seeds lose viability after about five years, while broadleaf weed seeds can survive for considerably longer as their seed coats are generally harder.
- As seed burial and the soil environment are key aspects of weed seed survival, cultivation, especially ploughing, and reduced tillage have both positive and negative impacts on the seedbank and the type and amount of weeds that germinate and emerge.

In annual arable crops, such as maize, most weeds are also annuals as their life cycle matches that of the crop, so their populations can quickly build up if unmanaged. The evolutionary strategy for all annual plants is to 'be seeds'. Seeds are the longest-lived part of the plant's life cycle, lasting years to decades, in comparison the weed plant often lives only a few weeks or months. Therefore, the weed seedbank is the 'heart' of the annual weed challenge and the focus of integrated weed management.

Many people mistakenly believe that the seedbank lasts many decades and little can be done to reduce it. In reality, soil is a very hostile environment for seeds, it is physically abrasive, chemically caustic, and biologically aggressive (seeds as a highly valuable food source for everything from bacteria to birds).

Trials have shown that up to 30% of new seed will germinate in the following spring, about 30% will be lost (predated or decayed in the first year) and the remainder will contribute to the long-term seed bank. Seed predation is greatest when weed seeds remain on the soil surface where they are easily accessible to foraging insects, rodents and birds. Areas of biodiversity on the farm provide habitats for beneficial insect foragers and crop residues in no-till systems provide shelter for foraging insects like ground beetles and crickets (but this must be balanced with their downside which is the provision of habitat for slugs). Buried seeds are less available to foragers, but large numbers succumb to attack from saprophytic soil microbes and seed pathogens, especially in wet soils. Seed coats, which are designed to protect the embryo from desiccation, weaken when the seed is subjected to wetting and drying as the soil environment changes.

Suicidal germination occurs when seeds germinate from too deep in the soil and seedlings exhaust their energy reserves and die before reaching the soil surface. However, many buried weed seeds are able to delay their germination until cultivation brings them closer to the soil surface.

The number of viable seeds in the seedbank thus declines exponentially if there is no new seed input. The best way to measure anything that undergoes exponential decay, for example radioactivity, is its half-life, not its total longevity. Looked at this way the half-life of the weed seed bank is typically only a few years, less for grasses. But exponential decay curves, like radioactivity, have very long 'tails', i.e. they take a long time to reach zero. The same is true of the weed seedbank, those few seeds that last for decades can then re-establish populations when conditions are right. For example, New Zealand research has shown that the seed of Scotch thistle (Cirsium vulgare), buried at depths greater than 40mm, persisted for 16 to more than 50 years and germinated once they were moved to the soil surface.

If weeds are allowed to go to seed the weed seedbank will increase exponentially. For weed seedbanks to decrease, the weed seed rain, i.e. the arrival of new seeds needs to be minimised. Annual weeds have the potential to produce vast numbers of seed, e.g. a single fathen plant can produce 500,000 seeds. Even a small fathen plant can produce 1,000 seeds, and even if only 10% of those seeds grow into weeds that themselves produce 1,000 seeds, then in four years there will be a million fathen plants descended from the first plant.

Thus, the weed seedbank is a lot more dynamic than commonly believed, it can both decrease and increase exponentially given the right conditions.

The third misconception around weed seed banks is that there is widespread movement of annual weed seeds. While some weed seeds do move across the landscape, e.g. from fence-lines into paddocks, among paddocks and between farms, in most cases the number of seeds moving around are insignificant compared to a paddock's weed seedbank. The ratio of a particular species' mobile seeds to the number of that species seeds in a given paddock's seedbank is what is important. If a paddock's seedbank already has lots of fathen seed in it then the introduction of a few more fat hen seeds will make no difference. However, weed seed movement is really critical in the case of (in order):

1. Biosecurity weeds
2. Herbicide resistant weeds
3. Weed species not already present
4. Windblown seeds

Biosecurity and herbicide resistance are covered in detail in earlier sections of this report.

There is surprisingly large variation in the weed species present in a given paddock and farm, such that some common weeds may be absent. Farms practicing good farm hygiene for biosecurity and resistance management gain the additional benefit of minimising the importation of weeds not already present. Species with windblown seeds, such as thistles, dandelions, fleabanes and willow herbs, can deposit significant numbers of seeds some distance from their source. Such windblown seeds are also called 'aerial seed banks'.

Managing the weed seedbank, i.e. minimising weed seed rain, and maximising depletion of the existing weed seedbank is at the heart of integrated weed management in annual cropping systems such as maize. A deliberate, multi-year, whole of farm, weed seedbank management strategy requires a diverse combination of techniques, which include:

- Tillage strategies
- Stale and false seed beds
- Herbicide programmes
- Mechanical weeding
- Post-harvest weed management,
- Cleaning of harvesting equipment and other machinery.

6.6 Tillage impacts on weed seedbanks

Most maize systems in New Zealand use either full inversion tillage or min-till. Minimum and no-till tend to shift the annual weed flora towards grass weeds, smaller seeded broadleafs, and perennial weeds. This is because in reduced tillage most weed seeds remain on or close to the surface where small seeds can easily germinate, but larger ones are more prone to predation. Perennials proliferate as they are not killed by tillage. In contrast, ploughing buries seeds. As grass seeds don't have the hard seed coat of broadleafs they typically only survive burial for around five years. Small seeded broadleafs are unable to emerge from depth after ploughing, but larger seeded weeds can, so tend to proliferate. Perennial weeds are also killed or set back by tillage.

While there is an overall desire to move to reduced tillage systems, due to benefits such as better soil structure, and reduced fuel use, the value of 'strategic ploughing' is becoming more important due to increasing herbicide resistance and biosecurity weed incursions. Strategic ploughing is where land that is mostly managed with min- or no-till, is strategically ploughed to bury weed seeds that have accumulated on the soil surface, to kill perennial weeds; the paddock will then then return to reduced tillage for three to five (or more) years, during which the buried weed seeds, particularly grasses, die. To better understand the impact of reduced tillage versus ploughing on the viability of common weeds in maize systems FAR and AgResearch undertook research to study weed seed viability in soil.

6.6.1 Buried weed seeds experiment

The experiment measured the seed viability of seven annual grass and two annual broadleaf weeds (see below for species) in soil, at two depths, over five years, across eight sites that represent the main New Zealand maize production areas: Northland, Waikato, Bay of Plenty, Gisborne, Hawke's Bay, Manawatu, Nelson and Canterbury . The sites had soil textures ranging from sands to clays, and different climates. Seeds were placed into fine mesh bags, which were then placed at 50 and 200 mm in soil filled perforated plastic tubes, which were then buried in the soil. Every year for five years a sub-sample of seeds were recovered and germinated in a glasshouse, and the number of seeds that germinated were turned into a percent germination based on the number of seeds originally placed in the mesh bags. The percent germination is thus a combination of a number of factors:

- The number of seeds that were viable when they were buried.
- The number of buried seeds that have undergone germination while buried (either with or without successful emergence), so cannot germinate again.
- The number of buried seeds that when dug up, were in sufficiently enforced ('deep') dormancy they would not germinate in the glasshouse.
- The direct and indirect (e.g. via soil biology) impact of soil texture on the viability of buried seeds and thus how many can germinate.
- The impact of climate (principally soil temperature and moisture) on the viability of buried seeds and thus how many can germinate.
- The effect of burial duration (time) on the viability of the buried seeds and thus how many can germinate.

Due to the many interacting factors affecting buried seed viability and successful germination it was not possible to disentangle the factors such as soil texture and climate in this experiment. However, from a farming perspective, the complexity is less important than how fast weed seed viability declined in general. Figure 23 shows the percent germination for each weed species at the two depths over the five years, across all locations, and a comparison of the grasses with the broadleaf weeds. Table 14 shows the germination rate of the weed species before burial.

Table 14. Initial percentage germination of the weed seed prior to burial.

Weed species	% germ
Apple of Peru	75%
Barnyard grass	90%
Broomcorn millet	74%
Rough bristle grass	87%
Smooth witchgrass	88%
Summer grass	87%
Thorn apple	69%
Witchgrass	68%
Yellow bristle grass	85%

Key to interpreting these results is that the germination percentage is a measure of the seeds maintaining viability, with the caveat that some may not germinate due to dormancy. Research has shown that putting seeds in containers, such as the mesh bags and perforated plastic pipes significantly reduces seed loss to larger organisms such as earthworms and arthropods, and thus helps maintain seed viability compared to unprotected seeds in the soil. These results are thus likely to show longer persistence than in real field conditions. With this in mind the results show a range of outcomes.

- None of the weeds had full germination rates before burial (below 60% up to 90%). Some seed will not have fully matured on the parent plant so will be never have been viable, some may require some time after being shed to become fully ripe and able to germinate, and some species produce a proportion of seed with primary dormancy so they will not germinate for some time after being shed.
- The overall germination percentage of each species after being buried needs to be viewed in the context of its pre-burial germination rates.
- Percent germination is higher for the deeper buried seeds, which means that more of these seeds are maintaining viability when buried at depth than when they are near the soil surface.
- In most cases there is a decline in germination over time, which indicates seeds are losing viability. This is more pronounced for shallow seeds, some of which may have germinated in the soil, so they clearly then cannot 're-germinate' in the glasshouse and thus be included in the percent germination counts.
- The viability of grasses is generally declining faster than the broadleafs.
- Apple of Peru shows an initial dip in viability in year two then increasing viability. This may be due to burial (at both depths) enforcing secondary dormancy which is not broken by the glasshouse germination method, and which then slowly reduces over the following years resulting in increasing germination.
- Barnyard grass, summer grass, and yellow bristle grass lose significant viability over the five years, indicating their viable seedbank is depleting.
- Witch grass, and the broadleafs apple of Peru and thorn apple have only a small loss of viability, indicating a persistent seedbank over the longer term.

The overall lessons from this experiment align with wider weed seedbank science.

- Shallow seedbanks decline faster due to germination and predation, as long as there are no new inputs of weed seed.
- Burying seed protects it from predation, prevents germination and enforces dormancy, such that the seed remains viable for longer.
- Grass seeds lose viability faster than broadleafs regardless of depth.
- Witchgrass stands out among the grasses as having only a small loss of viability at either depth over the five years.

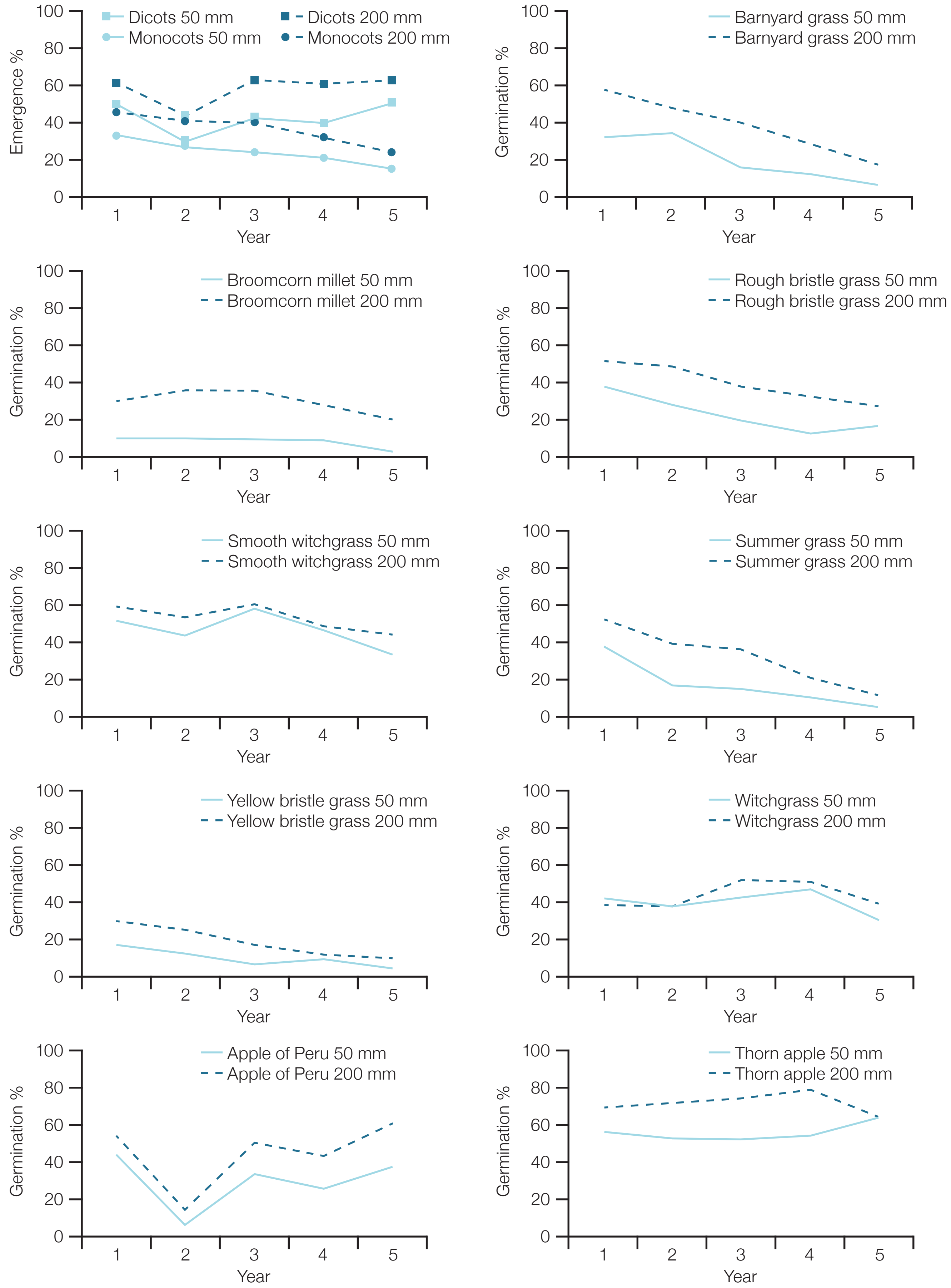

Figure 23. Percent germination of seven grass and two broadleaf weeds over five years that had been buried in soil at 50 and 200 mm at eight locations representing the main maize growing areas in NZ, and a comparison of the overall germination of the grasses verses broadleaf weeds. Grasses (monocots): Broom corn millet (*Panicum miliaceum*), Witchgrass (*Panicum capillare*), Smooth witchgrass (*Panicum dichotomiflorum*), Summer grass (*Digitaria sanguinalis*), Barnyard grass (*Echinochloa crus-galli*), Rough bristle grass (*Setaria verticillata*), Yellow bristle grass (*Setaria pumila*). Broadleafs (dicots): Thorn apple (*Datura stramonium*) broadleaf, Apple of Peru (*Nicandra physalodes*).

CASE STUDY

6.6.2 Full inversion tillage and cover crops

Alan Henderson

Alan farms 400 hectares near Te Awamutu, Waikato. The farm system includes dairy, cropping, sheep and beef, and horticulture.

Full inversion with a plough and power harrow is the main establishment method for maize crops on Alan Henderson's 400 ha farm in the Paterangi district near Te Awamutu. The farm's key enterprise is a dairy herd of 800 cows, but it also has a large cropping operation, with 80 ha of maize and 50 ha of chicory and turnips. Maize silage, chicory and turnips, as well as bought-in palm kernel, are used as supplementary feed for cows.

Maize is grown in the same paddocks each year, with some having been cropped for 60 years. Over time, weeds become more problematic in long-term maize paddocks, Alan says. "There's no shortcuts, you've got to do each spray programme thoroughly." The farm's main maize weeds are grass weeds, fathen, oxalis and summer grass.

While most of Alan's maize crops are established using full inversion with a plough and power harrow, he does some strip-till and minimum till. Preparation starts after harvest, with cover crops sown in all maize paddocks, whether for grain or silage. Cover crops, predominantly annual ryegrass, are grazed by cows or made into silage. Prior to sowing in maize, some areas, primarily the headlands, are sprayed with glyphosate (Group 9) and saflufenacil (Group 14 (Sharpen®)). "Where we plough, we don't spray the rest of the paddock, as full inversion buries the residues and weed seeds. Strip-till paddocks are fully sprayed out."

Under full cultivation, alachlor (Group 15) is applied as a pre-emergence herbicide, followed four to six weeks after emergence by a post-emergence herbicide to control broadleaf weeds, fathen, and some of the other more difficult to control weeds. "Unfortunately, oxalis is a difficult to kill weed. I haven't found a really good chemical to kill this yet."

After planting, strip-till crops are given a pre-emergence spray with glyphosate and alachlor, followed by a post-emergence spray, most likely mesotrione (Group 27) and atrazine (Group 5). "Under minimum and strip-till the paddock gets three applications and in most cases with full inversion, two applications. What we are doing with full inversion is the same philosophy as farmers did in the 1930s with the horse and plough. You are burying the weed seed burden and organic matter. You are also burying a lot of diseases that thrive in the organic matter on the surface of the soil." Maize crops are reliable under full inversion, Alan says. "It is still economical doing it this way and there is a lot less risk. You are far more assured of a better crop." Generally, the farm's maize grain crops yield 18 to 20 tonnes/ha and silage 26 to 27 tonnes/ha.

While annual ryegrass is the main cover crop, other cover crops tried over the years include mustard, radish, barley, oats, faba beans and clover. While Alan primarily grows cover crops to improve biological activity and organic matter in the soil, they can also help with weed management. "I got very good weed control when I used radish as it worked down to a nice mulch."

CASE STUDY

6.6.3 Strip-till, band spraying and cover crops

Paul Hunter

Paul farms 240 hectares near Te Awamutu, Waikato. The farm is a mixed system with maize (180 ha) and grass/clover silage and livestock (bulls, steers and wintering dairy cows). The soil is mainly well drained Mairoa ash and some heavier Puniu silt loam, with no cattle grazed on the heavier ground.

A shift from plough and power harrow to strip-till to establish maize on Paul Hunter's Waikato farm is not only bringing machinery cost and time savings and environmental benefits, it is also helping with weed management. For six seasons, a contractor strip-tilled one paddock on his farm, enabling Paul to observe and evaluate the system before purchasing his own equipment. "There are a lot of efficiencies with it, particularly with machinery, time and fuel that gave a quick return. There were environmental reasons to do it as well. It also conserves soil moisture. "As time has gone on, I'm sure we have had a yield lift as well because of it."

Some paddocks on the farm have been cropped consecutively since the early 1970s. The property is rolling country and erosion, particularly after rain events, was causing a loss of top soil. To remedy this Paul has been using strip-till on all paddocks since 2018, after investing in an eight-row Soil Warrior strip-till machine, made in the United States by Environmental Tillage Systems, Minnesota.

Maize silage is planted on 180 ha, followed by annual ryegrass, an annual ryegrass and annual crimson clover mix, or pure clover. The annual ryegrass is used to winter 200 dairy cows for six weeks and finish 150 steers. Paul trialled several cover crops between maize before settling on annual crimson clover. The pure stands of clover are not grazed and are part of the 120 ha of winter forage harvested for silage.

To help the Soil Warrior deal with the root mass from the annual ryegrass, the strips are sprayed with glyphosate (Group 9) in June, once the grass has recovered from the first grazing. Specially-made fully enclosed spray hoods are used to contain the spray on the strip. This means there is no over spray and the paddock can be used for grazing right up to a few days before strip-tilling starts. "This sprays out one-third of the paddock, so we can still have use of two-thirds of that grass to continue grazing or for silage. In paddocks which aren't grazed, we have a programme of strip sowing clover where the next planting row will go." Paddocks are then fully sprayed with glyphosate in mid-September, two to three weeks prior to strip-tilling and planting. This is followed by pre- and post-emergence sprays. Slug bait is applied in a band at planting. There have been no changes in the type of problem weeds and amount of weed pressure since strip-till was introduced.

In terms of cover crops, the observation is that pure clover is definitely having a beneficial effect in suppressing weeds, but not annual ryegrass. "There is definitely some symbiosis going on with the clover and the next maize crop. There are a lot of things going on that I don't understand yet. The observation is that it is a lot easier to manage as there doesn't appear to be the weed pressure or bug pressure and the crop looks a lot better."

For the first three years, Paul moved the strip 25 cm, but has changed to a 40 cm shift as its fits with his RTK GPS lines. This is alternated every year, so the strip doesn't become too acidic and fertiliser is more evenly distributed through the soil profile. The Soil Warrior carries and bands the base fertiliser in the strips.

6.7 Seedbed preparation - stale and false seedbeds

Following on from the use of ploughing for weed management, stale and false seedbeds are also powerful tillage based weed management techniques. They can substantially reduce the amount of weeds that need to be controlled in-crop both by herbicides and/or mechanical weeding, so markedly improving their efficacy, and reducing risk should they face challenging conditions. Where they are practical, i.e. sufficient time is available pre-planting, their use is highly recommended.

Both are based on cultivating a final seedbed but then delaying sowing to allow the weed flush to emerge. In the false seedbed the weed flush is killed with very shallow cultivation, less than 5 cm deep and ideally just a couple of centimetres. In the stale seedbed the weedlings are killed with herbicide, ideally of a different mode of action Group than is used in the crop and elsewhere in the rotation. The challenge with a false seedbed is finding equiment that will achieve a high weed kill but cultivate very shallow. The spring tine harrow and Einböck Aerostar-Rotation, would be the main options. See the FAR Arable Extra 136 "Non-chemical weed management – stale and false seedbeds" www.far.org.nz/resources/extra-136-non-chemical-weed-management-stale-and-false-seedbeds for more information.

6.8 Pre-emergence herbicides

Key points:

Factors that affect the success of a pre-emergence herbicide programme include:

- Planting time. Early maize crops are more likely to need a follow-up post-emergent herbicide.
- The weed spectrum: atrazine-resistant fathen (*Chenopodium album*) and nicosulfuron-resistant summer grass (*Digitaria sanguinalis*) are common and widespread in Waikato and Bay of Plenty and to an extent in Hawke's Bay.
- Late emerging summer weeds may germinate after the herbicides have dissipated.
- Soil characteristics. Tilth and organic matter levels can affect the adsorption of the herbicide.
- Rainfall. Adequate moisture is required to activate the herbicides or else they must be incorporated into the soil mechanically.
- Soil temperature and moisture. Herbicides break down faster under warm, moist soil conditions.
- Premature breakdown of the herbicide's active ingredient. This can be caused by chemical degradation (faster in acid), or herbicide volatilisation from wet soils.
- Enhanced microbial degradation. Some herbicide active ingredients can be more rapidly broken down to non-herbicidal by-products by soil microbes after several years of use in the same location.
- Crop residues. These can act as a barrier preventing the herbicide reaching the soil surface.
- Side-dressing fertilisers may disrupt the action of soil-applied herbicides.
- Maize is most sensitive to competition two to eight weeks after emergence. Weeds emerging during this period should be controlled with post-emergence herbicides before they become well established and set seed.

Weeds in New Zealand maize have most commonly been managed by a mixture of pre-emergence herbicides. These herbicides control weeds as they germinate, before they emerge. A successful pre-emergence programme provides weed control during the sensitive time for the crop, from emergence to canopy closure. However, due to issues including herbicide resistance and increased microbial degradation, pre-emergence herbicides are not as effective as they once were and therefore post-emergent herbicides may also be required.

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

There are several effective pre-emergence herbicide combinations. One that is widely used is a mixture of a triazine herbicides, such as atrazine (Group 5) or terbuthylazine (Group 5), for broadleaf weed control, and a chloroacetanilide such as acetochlor (Group 15) or metolachlor (Group 15) for the control of grass weeds. However, this combination has led to widespread resistance of fathen to atrazine. For these and other difficult to manage broadleaf weeds the triazines have been successfully replaced by saflufenacil (Group 14 (Sharpen®)).

The pre-emergence herbicide mixture is applied to soil where it must be activated before it can be taken up by the emerging weed seedlings. Activation is achieved by one of three means:

1. Soil incorporation to a depth of 7-10 cm as soon as possible after application.
2. Rain or irrigation.
3. A wet soil surface (if the soil surface is wet at the time of application, activation will occur without 1 or 2).

Herbicides that control broadleaf weeds are mostly absorbed through the roots and therefore must be distributed in the root-zone. Grass weed herbicides are absorbed through the emerging coleoptile and therefore need to be concentrated near the soil surface. With rainfall, this is achieved naturally as the grass herbicides are less soluble than the broadleaf herbicides so remain closer to the surface while the broadleaf herbicides move down into the root zone. If the herbicides are to be incorporated for activation, incorporation depth is critical. Incorporating too deep will place the herbicides below the weeds' germination depth (waste of product) and their dilution through too much incorporation will reduce their efficacy.

Both groups require moisture for activation so soil moisture levels should be good or the application should be timed when rain is likely, or use irrigation where available.

In reduced tillage crops, the crop residue may act as a mulch to suppress weeds. If herbicides are required it is important to realise that their efficacy may be reduced by the amount of crop debris on the soil surface. This debris is a physical barrier to the herbicide, preventing good contact with the soil. A post-emergent herbicide programme may be a better option in this situation.

The effectiveness and duration of activity of pre-emergence herbicides depends on a number of factors, including:

- The weed spectrum present including herbicide resistant weeds e.g. atrazine (Group 5) resistant fathen
- Tilth and organic matter levels can affect the adsorption of the herbicide
- Soil temperature, which effects microbial degradation
- Breakdown of the herbicide's active ingredient by chemical degradation, photo-decomposition and herbicide volatilisation
- Disruption of the chemical barrier by fertiliser side dressing

After the pre-emergence herbicide programme, it is important to assess how well weeds are being controlled, so post-emergent herbicides can be applied if necessary. Early sown crops are more likely to need follow-up post-emergent treatments because their time until canopy closure is longer than in a later sown crop.

If a pre-emergence herbicide programme fails and environmental conditions are not to blame; then it is possible that enhanced microbial degradation of the herbicide is occurring. If most weed species die but one or a few species are unaffected, then it is possible that there is herbicide resistance.

Table 15 lists the selective pre-emergent herbicides registered for use in both maize silage and grain crops

Table 15. Selective pre-emergent herbicides registered for use in both maize silage and grain crops at September 2024. As new products come to market and existing products can be withdrawn it is essential to check current regulations.

Mode of Action group number	Mode of Action	Active ingredient	Type	Products	Primary weed target
3	Inhibits tubulin	pendimethalin	pre- and post-emergence	AGPRO pendimethalin Stomp® Xtra Strada®	Broadleaf + grasses
5	Photosystem II inhibition	terbuthylazine	pre- and post-emergence	Assett™ AGPRO terbuthylazine Magneto® Terb 500™ Terbaflo Timberwolf	Broadleaf
14	Inhibition of PPO	saflufenacil	pre-emergence	Sharpen®	Broadleaf
15	Cell division	acetochlor	pre-emergence	Ace™ Acetoken Acierto® Agcare® acetochlor AGPRO acetochlor Donaghys acetochlor Joker® Maize Guard® Roustabout® Smart acetochlor Sylon®	Grasses + some broadleafs including: Amaranthus species, black nightshade, chickweed, redroot, Scotch thistle, seedling dock, shepherd's purse, stinking mayweed, rayless mayweed, twin cress
		alachlor	pre-emergence	Alaken Corral® Cyclone® Merit® Taipan® Encaps®	Grasses + some broadleaf, including: black nightshade, fathen, redroot
		dimethenamid	pre-emergence	Frontier®	Grasses + some broadleafs including: apple of Peru, black nightshade, fathen, redroot, seedling dock, spurrey, twin cress, willow weed
		metolachlor	pre-emergence	Guvnor™ Gold Metoken Gold Super Maestro	Annual grasses
		propachlor	pre-emergence	Ramrod®	Grasses + some broadleaf, including chickweed and groundsel. Only susceptible at higher rates: fathen and redroot
27	Inhibits HPPD enzyme	mesotrione	pre- and post-emergence	AGPRO Mesotrione Dominator® Donaghys Lektor Mesoflex® Primiera®	Broadleaf including: Bathurst bur, black nightshade, chickweed, dandelion, fathen, fennel, fishtail oxalis, Galinsoga, hairy nightshade, hemlock, mallow, redroot, seedling docks, spurrey, stagger weed, twin cress, willow weed and wire weed

6.8.1 Herbicide residues

Effective weed management with persistent herbicides is a balancing act between having the herbicide in the soil long enough for it to control weeds during the season of application and it disappearing before it can impact on a susceptible following crop.

Many factors relating to the soil, the climate and characteristics of the herbicide will affect its breakdown and dissipation. Occasionally, the active ingredient in the herbicide can persist in the soil and cause problems for the following crop. Examples have been noted of herbicide residual damage in newly establishing autumn crops following maize silage. This damage can often be related to the timing of the last herbicides in the crop and to soil and climatic conditions.

From 2009-2011 AgResearch scientists undertook trials examining the effect of rainfall and its timing on the persistence of nicosulfuron (Group 2) on a number of different soils. The conclusions were:

- When applied at the recommended label rate of 60 g active ingredient (a.i.)/ha, nicosulfuron persisted in the soil from six to more than 15 weeks. This depended on the soil type and the amount and timing of rainfall after application.
- The amount of rainfall within two weeks of herbicide application was the major influence on dissipation of nicosulfuron residues in all soils.
- Simulated heavy rainfall (50 mm) in the first week or two after application or for several consecutive weeks, was more effective in reducing residues than repeated light (10 mm) or moderate (25 mm) rainfall or heavy rainfall applied after two weeks.
- Residues of nicosulfuron disappeared faster in soils with low pH and high organic matter levels.

Growers must be aware of the risk of nicosulfuron residues if it has been dry in the month following application and if their soils have a pH greater than 7.

6.8.1.1 Testing for herbicide residues in soil

You can do a simple test to check for herbicide residues. Carefully take a slice of the top 50 mm of soil and place it in a seed tray. Then plant a quick growing, herbicide sensitive brassica species such as turnip or radish. Use some soil from a non-herbicide area for a comparison. Any problem herbicide residues will become apparent from checked growth and damage to the young brassica seedlings.

Application technique also comes into consideration with herbicide residues – try and minimise overlaps as much as possible. A double application could take 20% longer to safely dissipate.

6.8.1.2 Herbicide application

All herbicide applications, both pre- and post-emergence, require good practices to achieve a good result, i.e. dead weeds.

The most important practice is to read the label fully and to follow the instructions for timing, application rate and spray volume, soil conditions (tilth, soil structure and organic matter content), recommended adjuvants and personal and environmental safety requirements during mixing, application and wash-down.

All application equipment should be calibrated, and forward speeds should be linked to the terrain and ground conditions. One of the principle reasons for poor herbicide efficacy is boom flex and bounce when forward speeds are too fast.

Worn nozzles give poor coverage and should be replaced. Low pressure air induction (AI) nozzles are a good option as they produce larger droplets that are less prone to drift and more likely to reach their target before evaporating. Nozzle performance charts provide a good summary of the performance characteristics and should be available wherever you buy your spray equipment.

Application timing is very important. Pre-emergence herbicides must be applied before weeds emerge. Post-emergence applications must be applied before the weeds are too large and the maize canopy intercepts too much of the spray volume.

6.8.1.3 Interactions with the soil

The effectiveness of a herbicide after it has been applied depends on its concentration and persistence in the soil. These factors are affected by the properties of the herbicide, weather conditions, and soil factors such as texture, pH, moisture and organic matter.

Herbicides have electrical charges that cause them to bind to the positive or negative charges on soil and organic matter particles. This process is called adsorption and it varies with soil pH, soil organic matter content, and climate. Soils with high cation exchange capacities (CEC), high levels of organic matter and/or clay are the most adsorptive. These soils may require higher rates or more frequent herbicide applications than sandy and coarse soils. Coarse, sandy soils are less adsorptive and herbicides will be more effective. However, their persistence might be reduced during heavy rain. Herbicide efficacy may be reduced in cloddy and in light fluffy soils.

Herbicides can be lost from the soil profile by leaching and surface run-off. Soil structure and texture and the solubility of the herbicide affects the risk of leaching losses and care must be taken to prevent the contamination of ground-water by leached herbicides.

7. IWM- Reducing weed impact on the crop

Key points:

- The second stage to target weeds via integrated weed management is when they are growing in the crop.
- Intercropping is an old technique whereby other plants are grown with the crop.
- Fertiliser timing and placement can have considerable impacts on weed populations.
- Post-emergence herbicides are important for controlling weeds that have escaped control by pre-emergence herbicide or have emerged later.
- Mechanical weeding is increasingly mainstream, with some of the world's largest agricultural machinery companies now offering machines, that can be used alone or in combination with herbicides.

Reducing weed impacts on the crop is the second stage in the IWMPRAISE Integrated Weed Management approach (Figure 1). It is typically the largest weed management focus, particularly in the first weeks after crop emergence.

7.1 Intercropping

Intercropping is the deliberate growing of two or more species of plants together. For example, prior to the advent of selective herbicides, maize and soybean were always intercropped in the USA. The intercrop plants can both be cash crops (as per maize and soybean) and/or non-cash crops, for example white clover grown underneath maize. Intercropping is not the same as cover cropping (Section 6.2). Cover cropping is focused on protecting the soil when maize (the cash crop) is not present, whereas, intercropping is about growing other plant species at the same time as the maize to gain benefits, such as nitrogen fixation.

Weed management can be a key benefit of intercropping. In the above example of undersowing maize with white clover, the clover suppresses weeds by shading the soil inhibiting weed seed germination, competing with weeds that do establish and providing habitat for weed seed predators such as carabid beetles. Intercropping is of increasing interest internationally. FAR has undertaken some initial research into maize intercropping, including using white clover as a perennial living mulch and strip-cropping maize into it, and relay sowing intercrops / catch crops to reduce nitrate leaching post-harvest. Intercropping in maize is a research focus for FAR.

7.2 Fertiliser / nutrient management

Improving nutrient management and application via the Four Rs (Right product, Right rate, Right place and Right time) is becoming increasingly important for environmental and financial reasons. It also has an important role to play in weed management, as optimal nutrient and pH levels to support a good crop that can compete with weeds.

Maize nutrient demand, particularly for nitrogen (N), varies over the crop's life. Applying fertiliser to match crop demand allows the crop to take the greatest share of the fertiliser. By contrast, as maize has limited N requirements in the first few weeks post-emergence, N applied at establishment will be used by newly germinating weeds, not the crop.

In a similar vein, broadcast fertiliser has to be dissolved and infiltrate through the soil surface to reach maize roots which are deeper in the soil. Newly germinated weeds, especially from small seeds, have their roots right at the soil surface so are able to take up the nutrients as they infiltrate, giving them a competitive advantage. Banding of fertilisers next to the crop row, means that weeds away from the band cannot access those nutrients, and weeds next to, and under, the band may be scorched. Better still is injecting (knifing) fertilisers into the soil, as this maximises the amount captured by the maize while reducing losses though volatilisation and surface runoff.

7.3 Post-emergence herbicides

Key points:

- Pre-emergence herbicides are becoming less effective, and often require a follow-up post-emergence herbicide.
- Achieving sufficient weed control with post-emergence herbicides is more complicated.
- Post-emergence herbicides have a more limitations than pre-emergence herbicides.
  - Broadleaf weeds should be sprayed before they are 10 cm high.
  - Grass weeds should be sprayed before they tiller.
- It is better to spray too early than too late. Weeds emerging with the crop are more competitive than those that emerge later. Larger weeds are also harder to kill.
- Always use sprayers set up for interrow spraying. Target the weed and don't waste spray by spraying the maize plants.
- An early post-emergent application of mesotrione (Group 27) or topramezone (Group 27) followed two to four weeks later by nicosulfuron (Group 2) provides similar weed control to a pre-emergent treatment of acetochlor (Group 15) and atrazine (Group 5). Topramezone (Group 27) can also provide similar levels of efficacy.

Pre-emergence herbicide mixtures with soil-residual action have been the key tool for effective weed control in maize crops. However, increasingly these are not controlling all weeds (due to enhanced rates of microbial degradation and resistance). In addition, with an increased focus on preventing weed seed rain as part of integrated weed management, post-emergent herbicides may be needed to achieve sufficient weed control. However, compared with pre-emergence herbicides, post-emergence herbicides:

- Control a narrower spectrum of weeds,
- Control weeds for a shorter period of time,
- Are sensitive to weed size and shape,
- Are affected by crop size (the crop canopy can limit herbicide application and penetration),
- Are less effective under adverse weather conditions,
- May have residue carry-over problems in some soils, if applied very late or in dry years.

Therefore, achieving sufficient weed control with post-emergence herbicides is more complicated.

7.3.1 Three year (2010-13) post-emergence maize herbicide research project in Waikato and Bay of Plenty

Increasing issues of enhanced microbial degradation and resistance to pre-emergence herbicides led to a significant research project on post-emergent herbicides in maize. The project, led by AgResearch and funded via MPI's Sustainable Farming Fund, was undertaken from 2010-13, on seven sites in the Bay of Plenty and Waikato. It included (what were then new) chemistries such as topramezone (Group 27), and investigated enhanced microbial degradation of pre-emergent herbicides. Although this research is now over a decade old, the results are still fully applicable as there have been very few additions or losses of herbicide chemistry in the intervening period.

The trials were mostly undertaken on farmers' fields in real maize crops, using small plots and hand harvest. Two sites were on FAR's Northern Crops Research Site (NCRS) and Pioneer's Rukuhia research site, again, as part of a whole paddock maize crop (Table 16).

Table 16. Site details for the three year (2010-13) post-emergence herbicides in maize research project in the Waikato and Bay of Plenty. NCRS = Northern Crops Research Site. Weed density: v.high >2000, high 1000-2000, med-high 600-1000, med 300-600, med-Low 100-300, Low <100 plants / m^2.

Year start	Region	Location	Site description	Weed type	Weed density
2010	Bay of Plenty	Ōtamarākau	Commercial farm	Grass	V.high
2010	Waikato	Matamata	Commercial farm	Mix	Med
2010	Waikato	Pārāwera	Commercial farm	Broadleaf	Low
2011	Waikato	Rukuhia	Pioneer research site	Mix	Med
2011	Bay of Plenty	Ōtamarākau	Commercial farm	Grass	High
2012	Bay of Plenty	Ōtamarākau	Commercial farm	Grass	High
2012	Waikato	NCRS	FAR research site	Mix	Med-Low

Table 17. All herbicide active ingredients, used in the three year (2010-13) post-emergence herbicides in maize research project in the Waikato and Bay of Plenty.

Herbicide active ingredient	Abbreviation	Group	Example product name
acetochlor	aceto	15	Roustabout®
atrazine	atrz	5	Gesaprim®
bromoxynil	brom	6	Emblem® Flo
dicamba	dicam	4	Banvel®
diquat	diquat	22	Spray Grow
fluthiacet-methyl	fluth	14	Cadet®
mesotrione	meso	27	Callisto®
nicosulfuron	nico	2	Latro® WG
paraquat	para	22	Spray Grow
primisulfuron	primi	2	Beacon
topramezone	topra	27	BAS 670

There was a large variation in weeds among the sites. The Bay of Plenty (BoP) site was on the same farm but different paddocks in different years had high to very high, grass dominated weeds. The two sites with a mix of grass and broadleaf weeds had medium weed levels. The one site where broadleaf weeds were dominant had the lowest level of weeds (Table 16). Table 17 lists all herbicides active ingredients, mode of action groups and example product names used in the trial.

Table 18 details every herbicide treatment used in the research project over all three years and seven sites. It details the herbicide active ingredient and whether they were used as a tank mix or in a sequence; the time of application in weeks post-crop emergence (WPE); the dominant weed type present (grass, broadleaf or a mixture); and the number of times the treatments were used across all three years and seven sites. Herbicide treatments were partly based on the weed types and numbers that emerged, e.g., grass

Table 18. All herbicide treatments used in the three year (2010-13) post-emergence herbicides in maize research project in the Waikato and Bay of Plenty. Abbreviation = herbicide name abbreviations used in the rest of this book. A '+' sign between herbicides denotes a tank mix, a '>' sign between herbicides denotes sequential applications. WPE = weeks post-(crop) emergence. '0 WPE' = pre-emergent herbicide. The pre-emergence herbicides atrazine + acetochlor are included as the standard maize herbicide treatment, both as a stand-alone treatment and in sequence with post-emergence herbicides. Group = herbicide Mode of Action Group. 'Application WPE' is broken down by weed type, on which herbicide choices were based. A comma (,) separates different treatments, both within the same trial and among different trials (both locations and years), showing which treatments were used the most often.

	Herbicide treatments			Application WPE		
Abbreviation	Pre-emergence 0 WPE	Post-emergence 1-8 WPE	Group	Broadleafs	Grass	Mix
Atrz + aceto	atrazine + acetochlor		5+15	0	0	0
Atrz > nico		atrazine > nicosulfuron	5>2	3>8		2>3
Atrz + aceto > atrz + meso	atrazine + acetochlor	atrazine + mesotrione	5+15>5+27		0>3	
Atrz + aceto > nico	atrazine + acetochlor	nicosulfuron	5+15>2		0>4	0>3
Atrz > nico x 2		atrazine > nicosulfuron > nicosulfuron	5>2		3>5>7	
Atrz > primi + dicam > nico		atrazine > primisulfuron + dicamba > nicosulfuron	5>2+4>2		3>5>7	
Brom		bromoxynil	6	8		3
Brom + nico		bromoxynil + nicosulfuron	6+2	8		3
Dicam		dicamba	4	8		
Dicam + nico		dicamba + nicosulfuron	4+2			3
Meso + atrz		mesotrione + atrazine	27+5	3	1, 2, 3	2, 3, 4, 5
Meso + atrz > nico		mesotrione + atrazine > nicosulfuron	27+5>2	3	2>5, 1>4, 2>4, 3>5, 3>6	2>4, 2>5
Meso + nico		mesotrione + nicosulfuron	27+2		2, 3, 4	3
Nico		nicosulfuron	2	3	1, 2, 3	2, 3, 5
Nico x 2		nicosulfuron > nicosulfuron	2			2>4
Nico x 3		nicosulfuron > nicosulfuron > nicosulfuron	2		3>5>7	
Nico + fluth		nicosulfuron + fluthiacet-methyl	2+14			4, 5
Nico x 2 > meso + atrz		nicosulfuron > nicosulfuron > mesotrione + atrazine	2>27+5		3>6>7	
Nico + primi > nico		nicosulfuron + primisulfuron > nicosulfuron	2+2		5>7	
Nico + primi > nico + primi		nicosulfuron + primisulfuron > nicosulfuron + primisulfuron	2+2		3>5	
Para + diquat		paraquat + diquat	22+22		2, 3, 4	2, 3, 5
Topra		topramezone	27		1, 2	
Topra + atrz		topramezone + atrazine	27+5		2, 3, 4	3
Topra > nico		topramezone > nicosulfuron	27>2		1>6, 2>6	
Untreated	Untreated	Untreated	N/a	Untreated	Untreated	Untreated

dominant sites were targeted with grass herbicides, and sites with high weed pressures received more applications, while also ensuring that a range of herbicides, particularly newer and more effective chemistries were tested more often.

Note that as different methods were used in each year to covert plot measurements of yield to yield per hectare, year-to-year results cannot be compared. Therefore, the most relevant comparisons are among the different herbicide treatments in the same year and site, i.e. in an individual trial. The 2010 plot to hectare yield conversion had specific issues so that the 2010 absolute yield data are not presented. The results presented in Tables 19 to 25 show the average combined yield of both silage and grain as a percentage of the untreated control for each trial. Silage and grain yields show consistently similar responses to each herbicide treatment within a trial, so combining the two yields highlights which herbicide treatments achieved the largest yield increases for the particular trial conditions e.g. weed pressure. Figures 24 to 27 show the individual absolute yields of grain and silage for each trial site and year, for each herbicide treatment in that trial. The table and figure for each trial are presented next to each other.

Table 19. Combined average yield of grain and silage as a percentage of the untreated (no herbicide) control at the 2010 Pārāwera trial site in Waikato under a low level of broadleaf weeds in the three year (2010-13) post-emergence herbicides in maize research project in the Waikato and Bay of Plenty. Herbicide abbreviations: aceto = acetochlor G18, atrz = atrazine G5, brom = bromoxynil G6, dicam = dicamba G4, meso = mesotrione G27, nico = nicosulfuron. A '+' sign between herbicides denotes a tank mix, a '>' sign between herbicides denotes sequential applications. The number in brackets is the weeks post-(crop) emergence (WPE) that the herbicides were applied. '0 WPE' = pre-emergent herbicide.

Herbicide treatments	Average % yield increase over control
Nico (3)	14%
Nico x 2 (3,8)	12%
Atrz + aceto (0)	11%
Meso + atrz (3)	11%
Brom + nico (8)	9%
Meso + atrz (3) > nico (8)	8%
Brom (8)	6%
Atrz (3) > nico (8)	5%
Untreated	0%
Dicam (8)	-2%

Table 20. Combined average yield of grain and silage as a percentage of the untreated (no herbicide) control at the 2010 Matamata site in the Waikato under medium weed pressure of a mixture of grasses and broadleafs in the three year (2010-13) post-emergence herbicides in maize research project in the Waikato and Bay of Plenty. Herbicide abbreviations: aceto = acetochlor G18, atrz = atrazine G5, brom = bromoxynil G6, dicam = dicamba G4, meso = mesotrione G27, nico = nicosulfuron G2. A '+' sign between herbicides denotes a tank mix, a '>' sign between herbicides denotes sequential applications. The number in brackets is the weeks post-(crop) emergence (WPE) that the herbicides were applied. '0 WPE' = pre-emergent herbicide.

Herbicide treatments	Average % yield increase over control
Atrz + aceto (0) > nico (3)	61%
Nico (2)	58%
Meso + atrz (2) > nico (4)	53%
Nico x 2 (2,4)	52%
Atrz (2) > nico (3)	52%
Brom (3)	47%
Brom + nico (3)	46%
Meso + atrz (2)	42%
Dicam + nico (3)	36%
Untreated	0%

Table 21. Combined average yield of grain and silage as a percentage of the untreated (no herbicide) control at the 2010 Ōtamarākau site in Bay of Plenty under very high grass weed pressure in the three year (2010-13) post-emergence herbicides in maize research project in the Waikato and Bay of Plenty. Herbicide abbreviations: aceto = acetochlor G18, atrz = atrazine G5, dicam = dicamba G4, meso = mesotrione G27, nico = nicosulfuron G2, primi = primisulfuron G2. A '+' sign between herbicides denotes a tank mix, a '>' sign between herbicides denotes sequential applications. The number in brackets is the weeks post-(crop) emergence (WPE) that the herbicides were applied. '0 WPE' = pre-emergent herbicide.

Herbicide treatments	Average % yield increase over control
Atrz + aceto (1) > atrz + meso (3)	4559%
Meso + atrz (3) > nico (6)	3732%
Meso + atrz (3) > nico (5)	3574%
Nico x 2 (3,6) > meso + atrz (7)	3456%
Nico x 3 (3,5,7)	3223%
Atrz (3) > nico x 2 (5,7)	3173%
Nico + primi x 2 (3,5)	2740%
Nico + primi (5) > nico (7)	2598%
Atrz (3) > primi + dicam (5) > nico (7)	1437%
Untreated	0%

Table 22. Combined average yield of grain and silage as a percentage of the untreated (no herbicide) control at the 2011 Ōtamarākau site in the Bay of Plenty under high grass weed pressure in the three year (2010-13) post-emergence herbicides in maize research project in the Waikato and Bay of Plenty. Herbicide abbreviations: aceto = acetochlor G18, atrz = atrazine G5, meso = mesotrione G27, nico = nicosulfuron G2, topra = topramezone G27. A '+' sign between herbicides denotes a tank mix, a '>' sign between herbicides denotes sequential applications. The number in brackets is the weeks post-(crop) emergence (WPE) that the herbicides were applied. '0 WPE' = pre-emergent herbicide.

Herbicide treatments	Average % yield increase over control
Topra (1) > nico (6)	958%
Atrz + aceto (1)	920%
Topra (2) > nico (6)	893%
Meso + atrz (2) > nico (4)	830%
Topra (1)	795%
Meso + atrz (3) > nico (6)	779%
Meso + atrz (2)	776%
Topra (2)	771%
Meso + atrz (1) > nico (4)	768%
Nico x 2 (3,6)	715%
Nico x 2 (1,4)	686%
Nico (1)	677%
Nico x 2 (2,4)	670%
Nico (2)	648%
Meso + atrz (1)	640%
Nico (3)	634%
Meso + atrz (3)	608%
Untreated	0%

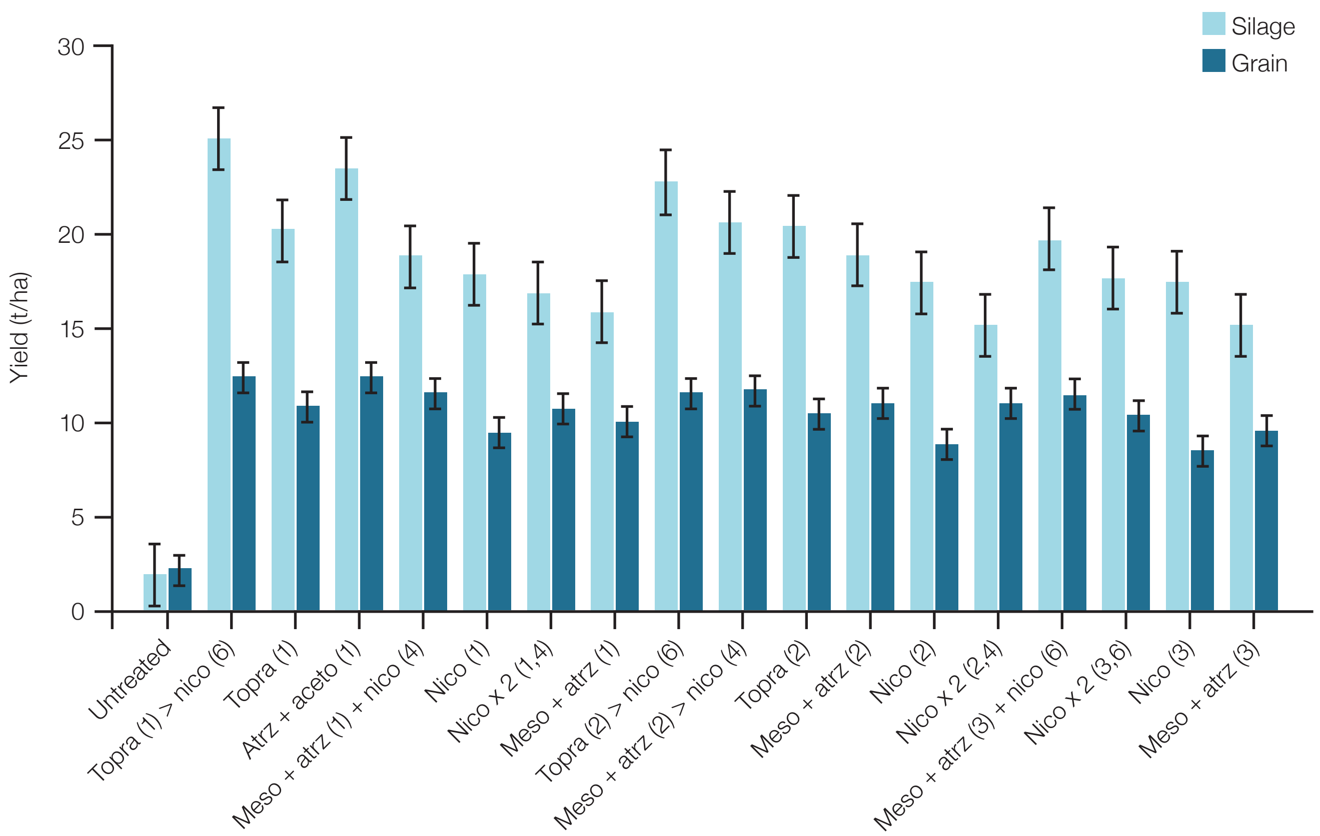

Figure 24. Yield (tonne / ha) for silage and grain at the 2011 Ōtamarākau site in the Bay of Plenty under high grass weed pressure in the three year (2010-13) post-emergence herbicides in maize research project in the Waikato and Bay of Plenty. Data analysis by general ANOVA, p=<0.001 for both silage and grain, error bars are 1 LSD, LSD0.05 3.388 for silage, 1.616 for grain. Herbicide abbreviations: aceto = acetochlor G18, atrz = atrazine G5, meso = mesotrione G27, nico = nicosulfuron G2, topra = topramezone G27. A '+' sign between herbicides denotes a tank mix, a '>' sign between herbicides denotes sequential applications. The number in brackets is the weeks post-(crop) emergence (WPE) that the herbicides were applied. '0 WPE' = pre-emergent herbicide.

Table 23. Combined average yield of grain and silage as a percentage of the untreated (no herbicide) control at the 2011 Rukuhia site in Waikato under medium weed pressure of a mixture of grasses and broadleafs in the three year (2010-13) post-emergence herbicides in maize research project in the Waikato and Bay of Plenty. Herbicide abbreviations: aceto = acetochlor G18, atrz = atrazine G5, fluth = fluthiacet-methyl G14, meso = mesotrione G27, nico = nicosulfuron G2. A '+' sign between herbicides denotes a tank mix, a '>' sign between herbicides denotes sequential applications. The number in brackets is the weeks post-(crop) emergence (WPE) that the herbicides were applied. '0 WPE' = pre-emergent herbicide.

Herbicide treatments	Average % yield increase over control
Meso + atrz (5)	62%
Meso + atrz (2)	53%
Meso + atrz (4)	48%
Nico (2)	47%
Nico (3)	44%
Nico + fluth (5)	42%
Atrz + aceto (0)	41%
Nico (5)	41%
Nico + fluth (4)	34%
Untreated	0%

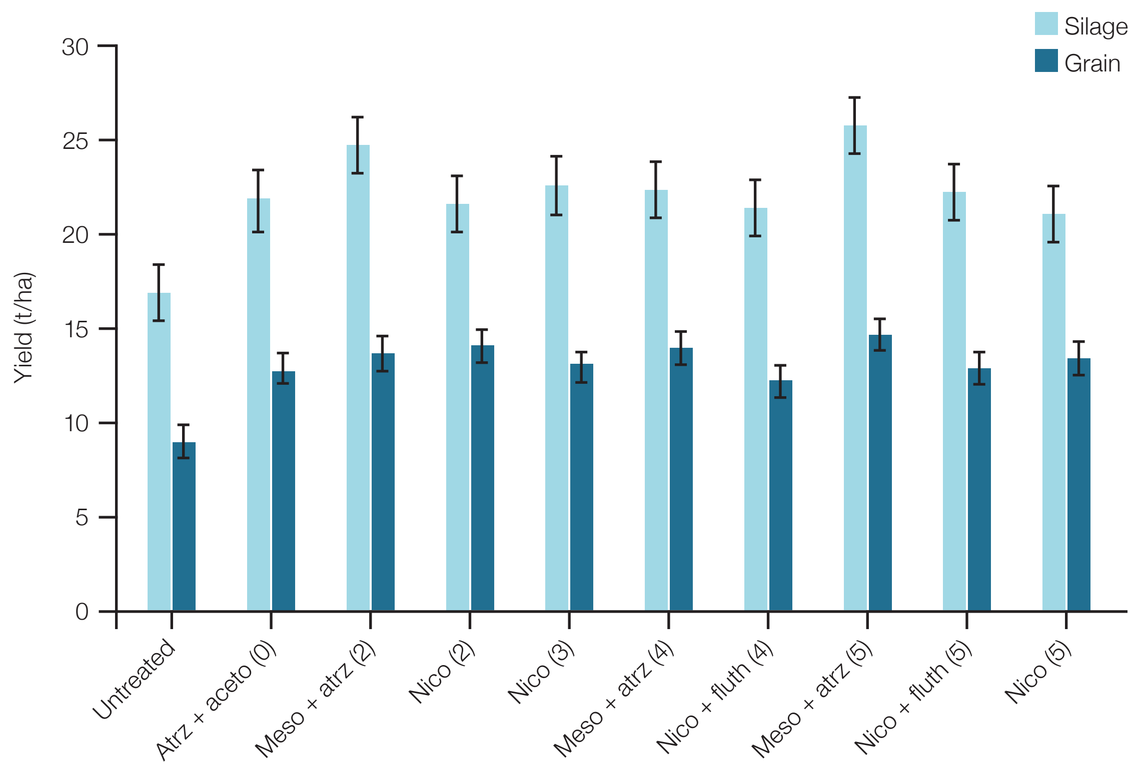

Figure 25. Yield (tonne / ha) for silage and grain at the 2011 Rukuhia site in Waikato under medium weed pressure of a mixture of grasses and broadleafs in the three year (2010-13) post-emergence herbicides in maize research project in the Waikato and Bay of Plenty. Data analysis by general ANOVA, p=<0.001 for both silage and grain, error bars are 1 LSD, LSD0.05 3.047 for silage, 1.821 for grain. Herbicide abbreviations: aceto = acetochlor G18, atrz = atrazine G5, fluth = fluthiacet-methyl G14, meso = mesotrione G27, nico = nicosulfuron G2. A '+' sign between herbicides denotes a tank mix, a '>' sign between herbicides denotes sequential applications. The number in brackets is the weeks post-(crop) emergence (WPE) that the herbicides were applied. '0 WPE' = pre-emergent herbicide.

Table 24. Combined average yield of grain and silage as a percentage of the untreated (no herbicide) control at the FAR Northern Crops Research Site in the Waikato under medium to low weed pressure of a mixture of grasses and broadleafs in the three year (2010-13) post-emergence herbicides in maize research project in the Waikato and Bay of Plenty. Herbicide abbreviations: aceto = acetochlor G18, atrz = atrazine G5, diquat = diquat G22, meso = mesotrione G27, nico = nicosulfuron G2, para = paraquat G22, topra = topramezone G27. A '+' sign between herbicides denotes a tank mix, a '>' sign between herbicides denotes sequential applications. The number in brackets is the weeks post-(crop) emergence (WPE) that the herbicides were applied. '0 WPE' = pre-emergent herbicide.

Herbicide treatments	Average % yield increase over control
Meso + atrz (2)	38%
Meso + atrz (5)	37%
Meso + atrz (3)	36%
Meso + nico (3)	34%
Atrz + aceto (0) > nico (3)	32%
Atrz + aceto (0)	28%
Para + diquat (3)	26%
Topra + atrz (3)	26%
Para + diquat (4)	25%
Nico (2)	24%
Para + diquat (2)	21%
Meso + atrz (2) > nico (5)	18%
Nico (5)	18%
Nico (3)	12%
Untreated	0%

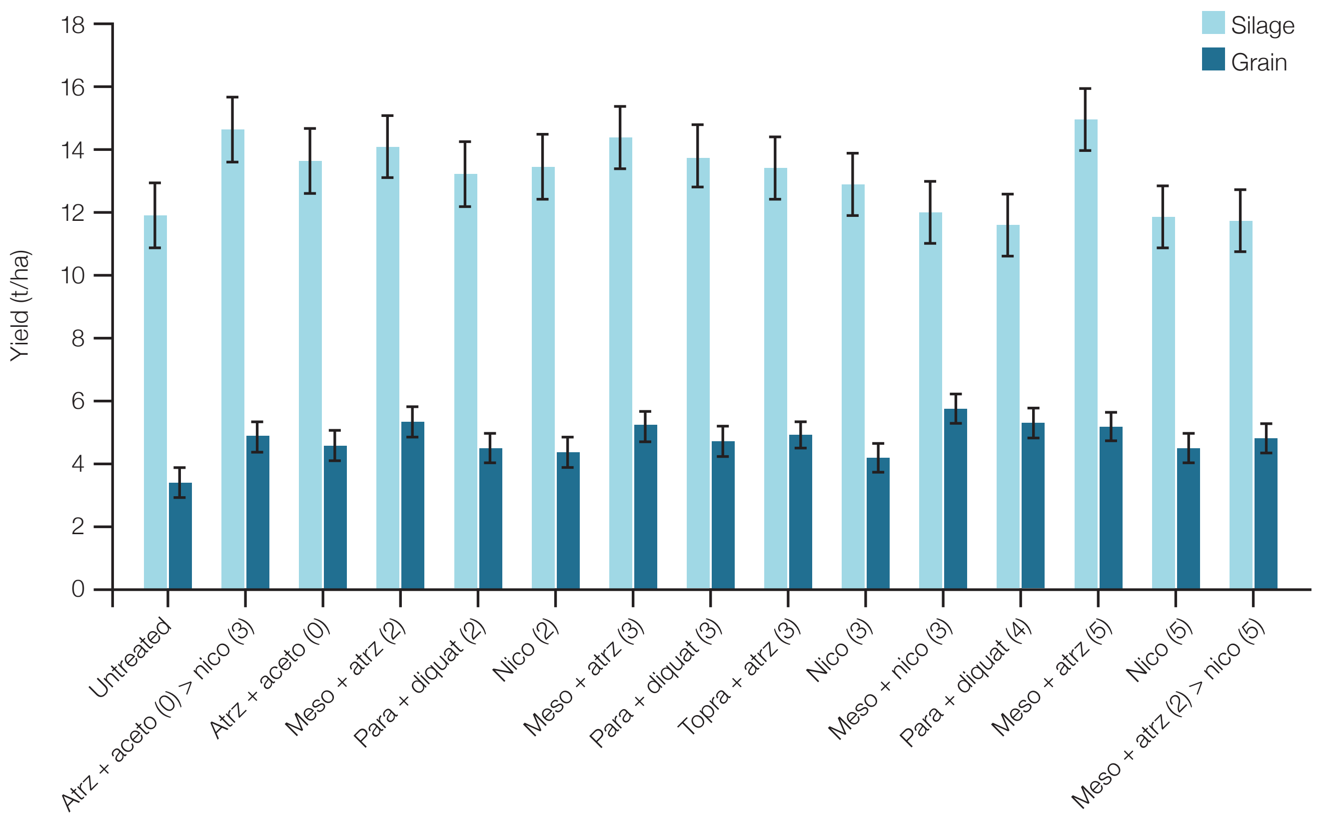

Figure 26. Yield (tonne / ha) for silage and grain at the FAR Northern Crops Research Site in the Waikato under medium to low weed pressure of a mixture of grasses and broadleafs in the three year (2010-13) post-emergence herbicides in maize research project in the Waikato and Bay of Plenty. Data analysis by general ANOVA, p=0.015 for silage and p=0.007 for grain, error bars are 1 LSD, LSD0.05 2.063 for silage, 0.9805 for grain. Herbicide abbreviations: aceto = acetochlor G18, atrz = atrazine G5, diquat = diquat G22, meso = mesotrione G27, nico = nicosulfuron G2, para = paraquat G22, topra = topramezone G27. A '+' sign between herbicides denotes a tank mix, a '>' sign between herbicides denotes sequential applications. The number in brackets is the weeks post-(crop) emergence (WPE) that the herbicides were applied. '0 WPE' = pre-emergent herbicide.

Table 25. Combined average yield of grain and silage as a percentage of the untreated (no herbicide) control at the 2012 Ōtamarākau site in Bay of Plenty under high grass weed pressure in the three year (2010-13) post-emergence herbicides in maize research project in the Waikato and Bay of Plenty. Herbicide abbreviations: aceto = acetochlor G18, atrz = atrazine G5, diquat = diquat G22, meso = mesotrione G27, nico = nicosulfuron G2, para = paraquat G22, topra = topramezone G27. A '+' sign between herbicides denotes a tank mix, a '>' sign between herbicides denotes sequential applications. The number in brackets is the weeks post-(crop) emergence (WPE) that the herbicides were applied. '0 WPE' = pre-emergent herbicide.

Herbicide treatments	Average % yield increase over control
Topra + atrz (2)	2032%
Atrz + aceto (0) > nico (4)	1883%
Meso + atrz (2) > nico (5)	1824%
Topra + atrz (3)	1789%
Meso + nico (2)	1667%
Para + diquat (2)	1519%
Meso + nico (3)	1480%
Topra + atrz (4)	1474%
Atrz + aceto (0)	1442%
Meso + atrz (3)	1398%
Para + diquat (4)	1068%
Para + diquat (3)	963%
Nico (3)	940%
Meso + nico (4)	627%
Untreated	0%

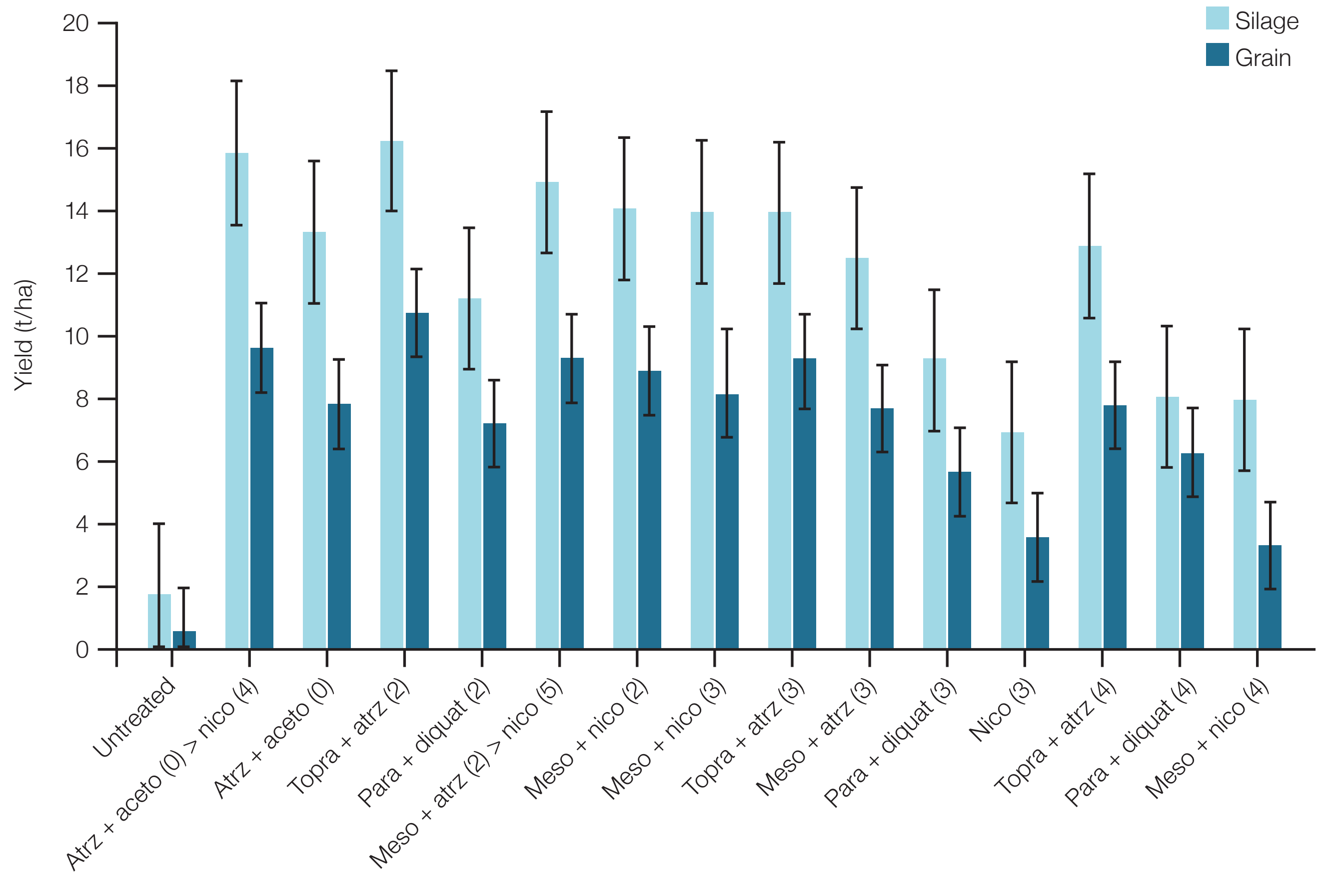

Figure 27. Yield (tonne / ha) for silage and grain at the 2012 Ōtamarākau site in Bay of Plenty under high grass weed pressure in the three year (2010-13) post-emergence herbicides in maize research project in the Waikato and Bay of Plenty. Data analysis by general ANOVA, p=<0.001 for both silage and grain, error bars are 1 LSD, LSD0.05 4.575 for silage, 2.866 for grain. Herbicide abbreviations: aceto = acetochlor G18, atrz = atrazine G5, diquat = diquat G22, meso = mesotrione G27, nico = nicosulfuron G2, para = paraquat G22, topra = topramezone G27. A '+' sign between herbicides denotes a tank mix, a '>' sign between herbicides denotes sequential applications. The number in brackets is the weeks post-(crop) emergence (WPE) that the herbicides were applied. '0 WPE' = pre-emergent herbicide.

7.3.1.2 Conclusions to 2010-13 post-emergence maize herbicide trials in Waikato and Bay of Plenty

The key lessons from the trials shown in Tables 19 to 25 and Figures 24 to 27 are that the yield response to herbicides, and therefore the return on investment (RoI) from using them, is strongly dependent on weed pressure. Low weed pressure resulted in little yield difference between the untreated control and all herbicide treatments, and therefore a low RoI, while at high weed pressure the yield of the untreated controls was very low, and therefore herbicides will provided a high RoI.

While RoI of herbicides on yield is currently the key factor driving herbicide use, within integrated weed management there also needs to be a focus on minimising weed seed rain. Large weed seedbanks result in large amounts of weed in following crops, which require greater herbicide use in future. This is clearly illustrated at the Ōtamarākau site in Bay of Plenty (Tables 19 - 25 and Figures 24 and 27). This means that where there are weeds present that are likely to go to seed later in the crop's life, applying a final herbicide nearer to crop canopy closure may also give an economic RoI.

The trials provided large yield variations among sites and years. This was due to differences in inherent soil fertility and the weather, for example 2011 was a drought year. Yields for both silage and grain follow the same pattern. This is expected, as high grain yield requires high maize plant biomass which is the same as high silage yield. The differences among herbicide treatments for each trial is more moderate, with fewer differences under lower weed pressure and the largest differences showing up under the higher weed pressures. Again, this is not surprising, as with low weed pressure, any differences in herbicide efficacy will be small, while at high weed pressures differences in herbicide efficacy will be more pronounced.

Distilling overall herbicide lessons from across all the trials is complex, mainly due to the different weed types (grasses and broadleafs require different herbicide approaches) and weed pressure. There is also inherent yield variation between sites and years due to different soils, weather etc. Within these limitations the overall lessons from the trials include:

Weeds that emerge with the crop are more competitive than those which emerge after establishment. This means it is essential to get in early and manage these weeds, as left uncontrolled they can have a large negative impact on maize plant growth, development and yield. Therefore, timing of post-emergence herbicides is critically important, especially if the pre-emergence treatment has not performed as expected. In general, post-emergence applications made at two to three weeks post-crop emergence perform better than when applied at week one or four or more weeks after crop emergence. The longer applications are delayed the more yield and weed control will decline.

An early post-emergent application of mesotrione or topramezone (both Group 27) followed two to four weeks later by nicosulfuron (Group 2) provided similar weed control to a pre-emergent treatment of acetochlor (Group 15) and atrazine (Group 5). Topramezone can also provide similar levels of efficacy. The standard pre-emergent herbicide atrazine, both as a pre- and post-emergent, was also part of the most effective treatments. So while atrazine faces issues with resistance and enhanced microbial degradation in soils where it is used repeatedly, it should still be considered to be part of an overall herbicide strategy. This can be seen in the effects of using just a pre-emergence herbicide treatment compared with a pre- and post-emergent treatment on yield relative to the untreated control (Table 26) and weed dry matter relative to untreated control (Table 28).

Table 26 shows that the combined pre- and post-emergent treatments at 3-4 WPE increased yield compared with a single pre-emergence herbicide treatment, with the increase in yield being more pronounced the higher the weed pressure. Likewise, Table 28 shows that weed dry matter measured at maize canopy closure is significantly reduced by adding a post-emergence treatment at 3-4 WPE compared with a sole pre-emergence treatment. The pre-emergent herbicide treatment was always atrazine (Group 5) + acetochlor (Group 18), while a range of different post-emergent treatments were used, as listed in Table 18.

While using both a pre- and post-emergence herbicide treatment will give the best overall weed control and maize yields, as the cover crop research (Section 6.2) has reported, the pre-emergence treatment can be substituted by an overwinter cover crop, allowing for a further reduction in herbicide use, particularly the staple pre-emergence atrazine (Group 5). This is becoming an important option as fathen has widespread resistance to atrazine (Group 5) and this herbicide is also subject to increased microbial degradation where it is repeatedly used on the same paddock.

Under good growing conditions, i.e. when it is warm and moisture is not limiting, maize can withstand a higher level of weed cover before exhibiting stress. As broadleaf weeds are less competitive than grass species. maize can withstand a higher level of broadleaf weed cover than of grass weeds before its growth is inhibited. Maize growth can be reduced by a grass weed cover of 20-50%; however, if the weed flora is mainly broadleaf species and growing conditions are favourable, the crop growth may not be affected until weed cover reaches well over 50%. Weed cover can be assessed with phone apps such as Canopeo (canopeoapp.com). This only applies to good growing conditions; under poor growing conditions much lower weed cover levels will impact yield. Further, as discussed earlier, minimising weed seed rain is an increasingly important component of integrated weed management, so while lower levels of weed cover may not cause a yield reduction in the current crop, if they produce a significant amount of seed, they will be an issue in the future.

Annual grass weeds

- Annual grass weeds need to be sprayed at an earlier growth stage than broadleaf weeds.
- Use FAR's Grass Weeds of Arable Crops Ute Guide to identify weeds.
- Summer grass is difficult to control and must be sprayed before tillering.
- Smooth witchgrass is not well controlled by mesotrione (Group 27), but nicosulfuron (Group 2) provides good control.

Table 26. Combined yield (%) of both grain and silage relative to untreated control of either a single application of pre-emergence herbicide treatment, or a sequence of one pre-emergence and one post-emergence herbicide treatment, 3-4 weeks post-emergence (WPE) under a range of weed pressures and types in the three year (2010-13) post-emergence herbicides in maize research project in the Waikato and Bay of Plenty. Weed pressure: V.high >2000, high 1000-2000, med-high 600-1000, med 300-600, med-Low 100-300, Low <100 plants / m^2.

	Weed type:	Broadleaf	Mix	Mix	Grass
	Weed pressure:	Low	Med-Low	Med	High
Herbicide treatment	**No. applications**				
Pre-emergence	1	11%	28%	41%	1181%
Pre+post-emergence 3-4 WPE	2		32%	61%	1882%

Table 27. Combined weed dry matter (%) relative to untreated control of either a single application of pre-emergence herbicide treatment, or a sequence of one pre-emergence and one post-emergence herbicide treatment, 3-4 weeks post-emergence (WPE), under a range of weed pressures and types in the three year (2010-13) post-emergence herbicides in maize research project in the Waikato and Bay of Plenty. Weed pressure: V.high >2000, high 1000-2000, med-high 600-1000, med 300-600, med-Low 100-300, Low <100 plants / m^2.

	Weed type:	Mix	Mix	Grass
	Weed pressure:	Med-Low	Med	High
Herbicide treatment	**No. applications**			
Pre-emergence		79%	3%	44%
Pre+post-emergence 3-4 WPE		4%	0%	10%

- Topramezone (Group 27) also give very good control of grass weeds.
- Post-emergent sprays have little residual activity.
- The best current treatment is mesotrione applied before grass weeds tiller (two to three weeks post-emergence) followed by nicosulfuron two to three weeks later.
- Using the correct adjuvant in the spray mix is very important for best control.

Annual broadleaf weeds

- Spray annual broadleaf weeds before they begin to interfere with crop growth.
- Use FAR's Broadleaf Weeds of Arable Crops Ute Guide to identify weeds .
- Base herbicide selection on the weeds present, most herbicides are very effective on broadleaf weeds.
- Spray timing is best determined by percentage ground cover of weeds.
- Spray dense infestations earlier to ensure good coverage of all weeds.
- Weeds will be more competitive in dry conditions ,so should be removed earlier.
- A single spray is usually sufficient to manage broadleaf weeds.
- If grass weeds are present, treat according to the grass weeds tips above.

Perennial weeds

- Perennial weeds should be sprayed later than annual weeds, as they require more leaf area to get a good kill.
- Ensure the target weed has adequate, three to six, leaves at spraying.
- Select herbicide according to weed(s) present.
- Use correct adjuvant and rate.

7.4 Selective post-emergence herbicides registered for use in maize

Table 28 lists the selective post-emergence herbicides registered for use in maize at the time of publication. As new products come to market and existing products can be withdrawn, it is essential to check current regulations.

As discussed in Section 3 it is essential to avoid repeatedly using the same herbicide group. Use tank mixes of different groups, rotate among groups in successive years, or ideally, use a sequence of tank mixes to minimise the selection of resistant weeds.

The effects of a range of herbicide treatments on different weed species at small and large sizes were assessed as part of the three year post-emergent herbicide trial (Tables 29 to 32).

Table 28. Selective post-emergent herbicides registered for use in both maize silage and grain crops at September 2024. As new products come to market and existing products can be withdrawn it is essential to check current regulations.

MoA group number	MoA	Active ingredient	Type	Products	Primary weed target
2	ALS inhibitor	flumetsulam	post-emergence	AGPRO flumetsulam Aim® Armada® Blast™ Donaghys flumetsulam Flame™ Kenstrike Officiate® Preside™ Rainbow & Brown Decision Smart Spear® Synery™ Flumet Valdo®	Some broadleafs, including: chickweed, spurrey, wild radish, hedge mustard cleavers, black nightshade, fathen, shepherds purse, mallow annual buttercup, creeping yellow cress, yellow gromwell stinking mayweed, wireweed, sorrel, field pansy, henbit, willow weed, oxeye daisy, giant buttercup, depending on size and rate
		halosulfuron	post-emergence	Sempra®	Purple nutsedge
		nicosulfuron	post-emergence	Adapt® Herbicide AGPRO Nicosulfuron Corvette™ Donaghys Formaize Latro®	Couch, fathen, summer grass, witch grass, bristle grass

Table continued over page

MoA group number	MoA	Active ingredient	Type	Products	Primary weed target
3	Inhibits tubulin	pendimethalin	pre- and post-emergence	AGPRO pendimethalin Stomp® Xtra Strada®	Broadleaf + grasses including: black nightshade, chickweed, cornbind, fathen, field pansy, fumitory, henbit, redroot, scarlet pimpernel, shepherd's purse, speedwell, spurrey, stinking mayweed, storksbill, wild oats, wireweed
4	Synthetic auxins	dicamba	post-emergence	Agcare® dicamba AGPRO dicamba Bandit® Cutlass® Dicam Dicamba Donaghys Rainvel Kamba® Performa™	Bindweed, California thistle, fathen
		clopyralid	post-emergence	AGPRO clopyralid Archer® Cobber® Donaghys Cronus Ken-Trel Multiple® Versatill® Vivendi® Void™	Bathurst burr, California thistle, Volunteer potato
5	Photosystem II inhibition	Atrazine	post-emergence	Atrazine And many generics	Annual broadleafs
		terbuthylazine	pre- and post-emergence	Assett™ AGPRO terbuthylazine Magneto® Terb 500™ Terbaflo Timberwolf	Annual broadleafs
6	Photosystem II inhibitor	Bromoxynil	post-emergence	Emblem®	A range of annual broadleafs at small growth stages
27	Inhibits HPPD enzyme	Mesotrione	pre- and post-emergence	AGPRO Mesotrione Dominator® Donaghys Lektor Mesoflex® Primiera®	Broadleafs including: Bathurst bur, black nightshade, chickweed, dandelion, fathen, fennel, fishtail oxalis, hairy nightshade, hemlock, Galinsoga, mallow, redroot, seedling docks, spurrey, staggerweed, twin cress, willow weed, wireweed + some grasses
		Topramezone	post-emergence	Arietta®	Broadleaf and some grasses including: apple of Peru, barnyard grass, black nightshade, broad-leaved dock (seedling), velvetleaf, chamomile, chickweed, dandelion, fathen, fleabane, groundsel, hemlock, large flowered mallow, scrambling speedwell, smooth witchgrass, summer grass, twin cress, white clover, willow weed, yellow bristle grass

Table 29. Herbicide efficacy for small grass weeds before tillering from the three year (2010-13) post-emergence herbicides in maize research project in the Waikato and Bay of Plenty. Source AgResearch.

	Groups	Timing	Summer grass (*Digitaria sanguinalis*)	Smooth witchgrass (*Panicum dichotomiflorum*)	Barnyard grass (*Setaria pumila*)	Yellow bristle grass (*Echinochloa pumila*)	Ryegrass (*Lolium* species)	Couch / twitch (*Elytrigia repens*)	Indian doab (*Cynodon dactylon*)	Mercer grass (*Paspalum distichum*)
Single application	**Groups**	**Timing**								
nicosulfuron	2	Post	Reasonable control *	Controlled	Controlled	Controlled	Controlled	Partial control	Not controlled	Partial control
mesotrione	27	Post	Reasonable control	Not controlled	Partial control	Partial control	Not controlled	Not controlled	Not controlled	Not controlled
topramezone	27	Post	Controlled	Reasonable control	Controlled	Controlled	Partial control	Partial control	Partial control	Partial control
dicamba	4	Post	Not controlled	Not controlled	Not controlled	Not controlled	Not controlled	Not controlled	Not controlled	Not controlled
bromoxynil	6	Post	Not controlled	Not controlled	Not controlled	Not controlled	Not controlled	Not controlled	Not controlled	Not controlled
primsulfuron	2	Post	Partial control	Partial control	Partial control	Not controlled	Not controlled	Controlled	Not controlled	Not controlled
flumetsulam	2	Post	Not controlled	Not controlled	Not controlled	Not controlled	Not controlled	Not controlled	Not controlled	Not controlled
atrazine	5	Pre+post		Partial control	Controlled	Partial control	Partial control			
Tank mixture										
mesotrione + atrazine	27, 5	Post	Controlled	Not controlled	Reasonable control	Not controlled	Not controlled	Not controlled	Not controlled	Not controlled
mesotrione + dicamba	27, 4	Post	Controlled	Not controlled	Not controlled	Not controlled	Not controlled	Not controlled	Not controlled	Not controlled
mesotrione + nicosulfuron	27, 2	Post	Controlled	Controlled	Controlled	Controlled	Not controlled		Not controlled	Reasonable control
nicosulfuron + primsulfuron	2, 2	Post	Reasonable control *	Reasonable control	Reasonable control	Reasonable control	Not controlled	Not controlled	Not controlled	Not controlled
nicosulfuron + fluthiacet-methyl	2, 14	Post	Reasonable control *	Controlled	Controlled	Controlled	Controlled	Partial control	Not controlled	Partial control
nicosulfuron + dicamba	2, 4	Post	Reasonable control *	Controlled	Controlled	Controlled	Controlled	Partial control	Not controlled	Partial control
nicosulfuron + atrazine	2, 5	Post	*							
topramezone + atrazine	27, 5	Post	Controlled	Controlled	Controlled	Controlled	Partial control	Partial control		
Split application										
mesotrione > nicosulfuron	27, 2	Post	Reasonable control *	Controlled	Controlled	Controlled	Controlled	Partial control	Not controlled	Partial control
mesotrione > atrazine + nicosulfuron	27, 5, 2	Post	Controlled *	Controlled	Controlled	Controlled	Controlled	Partial control	Not controlled	Partial control
nicosulfuron > mesotrione	2, 27	Post	Partial control *	Partial control	Partial control	Partial control	Partial control	Partial control	Not controlled	Partial control
dicamba > nicosulfuron	4, 2	Post	Reasonable control *	Controlled	Controlled	Controlled	Controlled	Partial control	Not controlled	Partial control
fluthiacet-methyl > nicosulfuron	14, 2	Post	Reasonable control *	Controlled	Controlled	Controlled	Controlled	Partial control	Not controlled	Partial control
bromoxynil > nicosulfuro	6, 2	Post	Reasonable control *	Controlled	Controlled	Controlled	Controlled	Partial control	Not controlled	Partial control

Key Contolled | Reasonable control | Partial control | Not contolled

* = not controlled if resistant populations exist.
Summer grass resisitant to nicosulfuron is common in Waikato and present in Bay of Plenty and Hawke's Bay.

Table 30. Herbicide efficacy for small grass weeds with multiple tillers from the three year (2010-13) post-emergence herbicides in maize research project in the Waikato and Bay of Plenty. Source AgResearch.

	Groups	Timing	Summer grass (*Digitaria sanguinalis*)	Smooth witchgrass (*Panicum dichotomiflorum*)	Barnyard grass (*Setaria pumila*)	Yellow bristle grass (*Echinochloa pumila*)	Ryegrass (*Lolium* species)	Couch / twitch (*Elytrigia repens*)	Indian doab (*Cynodon dactylon*)	Mercer grass (*Paspalum distichum*)
Single application	**Groups**	**Timing**								
nicosulfuron	2	Post	C *	C	R	R	R	P	N	P
mesotrione	27	Post	N	N	N	N	N	N	N	N
topramezone	27	Post	R	[illegible]	R	R	N	P	P	P
dicamba	4	Post	N	N	N	N	N	N	N	N
bromoxynil	6	Post	N	N	N	N	N	N	N	N
primsulfuron	2	Post	P	P	P	N	N	C	N	N
flumetsulam	2	Post	N	N	N	N	N	N	N	N
atrazine	5	Pre+post	R	P	C	P	P			
Tank mixture										
mesotrione + atrazine	27, 5	Post	P	N	R	R	N	N	N	N
mesotrione + dicamba	27, 4	Post	P	N	N	N	N	N	N	N
mesotrione + nicosulfuron	27, 2	Post	R	R	R	R	N		N	R
nicosulfuron + primsulfuron	2, 2	Post	P *	R	R	R	N	N	N	N
nicosulfuron + fluthiacet-methyl	2, 14	Post	R *	C	C	C	C	P	N	P
nicosulfuron + dicamba	2, 4	Post	R *	C	R	R	R	P	N	P
nicosulfuron + atrazine	2, 5	Post								
topramezone + atrazine	27, 5	Post	R	P	R	R	P	P	P	R
Split application										
mesotrione > nicosulfuron	27, 2	Post	C *	C	C	C	C	P	N	P
mesotrione > atrazine + nicosulfuron	27, 5, 2	Post	C *	C	C	C	C	P	N	P
nicosulfuron > mesotrione	2, 27	Post	P *	P	P	P	P	P	N	P
dicamba > nicosulfuron	4, 2	Post	C *	C	C	C	C	P	N	P
flufthiacet-methyl > nicosulfuron	14, 2	Post	C *	C	C	C	C	P	N	P
bromoxynil > nicosulfuro	6, 2	Post	C *	C	C	C	C	P	N	P

Key C = Contolled; R = Reasonable control; P = Partial control; N = Not contolled

* = not controlled if resistant populations exist.
Summer grass resisitant to nicosulfuron is common in Waikato and present in Bay of Plenty and Hawke's Bay.

Table 31. Herbicide efficacy for small broadleaf weeds from the three year (2010-13) post-emergence herbicides in maize research project in the Waikato and Bay of Plenty. Source AgResearch.

	Groups	Timing	Fathen (*Chenopodium album*)	Willow weed (*Persicaria maculosa*)	Black nightshade (*Solanum nigrum*)	Amaranthas (*Amaranthas powellii*)	Dock, seeding (*Rumex obtusifloius*)	Dock, regrowth (*Rumex obtusifloius*)	Oxalis (*Oxalis species*)	Wireweed (*Polygonum aviculare*)	Apple of Peru (*Nicandra physaloides*)	Twin cress (*Coronopus didymus*)	Thorn apple (*Datura stramonium*)	Portulaca (*Portulaca oleracea*)	Field bineweed (*Convolvulus arvensis*)	Velvetleaf (*Abutilon theophrasti*)	Hedge mustard (*Sisymbrium officinale*)	Scrambling speedwell (*Veronica persica*)	Galinsoga (*Galinsoga parviflora*)	Shepherd's purse (*Capsella bursapastoris*)
Single application	**Groups**	**Timing**																		
nicosulfuron	2	Post	R	C	R	C	C	P	R	P	C	C	C	R	P	P	C	R	R	C
mesotrione	27	Post	C	C	C	N	C	P	P	P	C	R	C	P	P	P	C	C	C	C
topramezone	27	Post	C	C	C	R	C	R	R	R	C	C	C	R	R	R	C	C	C	C
dicamba	4	Post	C *	C	C	P	C	R	P	R	R	R	C	R	C	R	C	P	R	R
bromoxynil	6	Post	C	C	C	R	C	N	P	P	C	R	C	P	C	R	C	R	R	R
primsulfuron	2	Post	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
flumetsulam	2	Post	R	P	R	C	N	N	N	R	N	N	N	N	N	N	C	N	N	C
atrazine	5	Pre+post	C *	C	R	R	C	P	N	N				R	R	P	C	R	C	C
Tank mixture																				
mesotrione + atrazine	27, 5	Post	C *	C	C	C	C	R	P	R	C	C	C	R	R	R	C	C	C	C
mesotrione + dicamba	27, 4	Post	C	C	C	C	C	C	P	R	C	C	C	R	C	C	C	C	C	C
mesotrione + nicosulfuron	27, 2	Post	C	C	C	C	C	P	R	P		R		R	P	P	C	R	C	C
nicosulfuron + primsulfuron	2, 2	Post	R	R	R	R	R	P	R	P		P			P	R	R	R	R	R
nicosulfuron + fluthiacet-methyl	2, 14	Post	C	C	C	C	C	P	R	P	C	C	C	R	P	P	C	R	C	C
nicosulfuron + dicamba	2, 4	Post	C	C	C	C	C	R	C	R	R	C	C	R	C	R	C	R	C	C
nicosulfuron + atrazine	2, 5	Post	*																	
topramezone + atrazine	27, 5	Post	C *	C	C	C	C	R	C	C	C	C	C	R	R	R	C	C	C	C
Split application																				
mesotrione > nicosulfuron	27, 2	Post	C	C	C	C	C	R	C	C	C	C	C	R	C	R	C	C	C	C
mesotrione > atrazine + nicosulfuron	27, 5, 2	Post	C *	C	C	C	C	R	C	C	C	C	C	R	C	R	C	C	C	C
nicosulfuron > mesotrione	2, 27	Post	P	P	P	P	P	P	R	P				R	P		P	P	P	P
dicamba > nicosulfuron	4, 2	Post	C	C	C	C	C	R	R	R	R	R	C	R	C	R	C	C	C	C
flufthiacet-methyl > nicosulfuron	14, 2	Post	C	C	R	C	C	P	R	P	C	C	C	R	P	P	C	R	C	C
bromoxynil > nicosulfuro	6, 2	Post	C	C	R	C	C	P	R	P	C	C	C	R	P	P	C	R	C	C

Key C = Contolled; R = Reasonable control; P = Partial control; N = Not contolled

* = not controlled if resistant populations exist.
Summer grass resisitant to nicosulfuron is common in Waikato and present in Bay of Plenty and Hawke's Bay.

Table 32. Herbicide efficacy for large broadleaf weeds from the three year (2010-13) post-emergence herbicides in maize research project in the Waikato and Bay of Plenty. Source AgResearch.

	Groups	Timing	Fathen (*Chenopodium album*)	Willow weed (*Persicaria maculosa*)	Black nightshade (*Solanum nigrum*)	Amaranthas (*Amaranthas powellii*)	Dock, seeding (*Rumex obtusifloius*)	Dock, regrowth (*Rumex obtusifloius*)	Oxalis (*Oxalis species*)	Wireweed (*Polygonum aviculare*)	Apple of Peru (*Nicandra physaloides*)	Twin cress (*Coronopus didymus*)	Thorn apple (*Datura stramonium*)	Portulaca (*Portulaca oleracea*)	Field bineweed (*Convolvulus arvensis*)	Velvetleaf (*Abutilon theophrasti*)	Hedge mustard (*Sisymbrium officinale*)	Scrambling speedwell (*Veronica persica*)	Galinsoga (*Galinsoga parviflora*)	Shepherd's purse (*Capsella bursapastoris*)
Single application	**Groups**	**Timing**																		
nicosulfuron	2	Post	Not contolled	Reasonable control	Not contolled	Reasonable control	Partial control	Not contolled	Reasonable control	Partial control	Not contolled	Partial control	Reasonable control	Not contolled	Partial control	Partial control	Contolled	Partial control	Partial control	Contolled
mesotrione	27	Post	Partial control	Reasonable control	Contolled	Not contolled	Partial control	Not contolled	Partial control	Not contolled	Partial control	Not contolled	Contolled	Not contolled	Partial control	Not contolled	Contolled	Reasonable control	Contolled	Contolled
topramezone	27	Post	Reasonable control	Reasonable control	Contolled	Reasonable control	Partial control	Partial control	Reasonable control	Partial control	Reasonable control	Reasonable control	Reasonable control	Reasonable control	Reasonable control	Partial control	Contolled	Contolled	Contolled	Contolled
dicamba	4	Post	Contolled	Reasonable control	Contolled	Partial control	Reasonable control	Reasonable control	Partial control	Reasonable control	Reasonable control	Reasonable control	Reasonable control	Reasonable control	Reasonable control	Partial control	Contolled	Partial control	Reasonable control	Reasonable control
bromoxynil	6	Post	Partial control	Partial control	Reasonable control	Reasonable control	Partial control	Not contolled	Partial control	Partial control		Reasonable control		Partial control	Partial control	Not contolled	Contolled	Reasonable control	Reasonable control	Reasonable control
primsulfuron	2	Post	Not contolled	Not contolled	Not contolled	Not contolled	Not contolled	Not contolled	Not contolled	Not contolled	Not contolled	Not contolled	Not contolled	Not contolled	Not contolled	Not contolled	Not contolled	Not contolled	Not contolled	Not contolled
flumetsulam	2	Post	Not contolled	Not contolled	Not contolled	Not contolled	Not contolled	Not contolled	Not contolled	Reasonable control	Not contolled	Not contolled	Not contolled	Not contolled	Not contolled	Not contolled	Reasonable control	Not contolled	Not contolled	Contolled
atrazine	5	Pre+post	Contolled	Contolled	Reasonable control	Reasonable control	Contolled	Partial control	Not contolled	Not contolled				Reasonable control	Reasonable control	Partial control	Contolled	Reasonable control	Contolled	Contolled
Tank mixture																				
mesotrione + atrazine	27, 5	Post	Contolled	Contolled	Contolled	Reasonable control	Reasonable control	Reasonable control	Partial control	Partial control	Reasonable control	Reasonable control	Reasonable control	Reasonable control	Reasonable control	Reasonable control	Contolled	Contolled	Contolled	Contolled
mesotrione + dicamba	27, 4	Post	Contolled	Contolled	Contolled	Contolled	Contolled	Contolled	Partial control	Reasonable control	Contolled	Contolled	Contolled	Reasonable control	Contolled	Reasonable control	Contolled	Contolled	Contolled	Contolled
mesotrione + nicosulfuron	27, 2	Post	Partial control	Partial control	Partial control	Reasonable control	Partial control	Partial control	Reasonable control	Partial control		Reasonable control		Reasonable control	Partial control	Partial control	Contolled	Reasonable control	Contolled	Contolled
nicosulfuron + primsulfuron	2, 2	Post	Not contolled	Not contolled	Not contolled	Reasonable control	Not contolled	Not contolled	Reasonable control	Partial control		Partial control			Partial control		Reasonable control	Partial control	Partial control	Partial control
nicosulfuron + fluthiacet-methyl	2, 14	Post	Reasonable control	Reasonable control	Reasonable control	Partial control	Partial control	Partial control	Reasonable control	Partial control	Reasonable control	Reasonable control	Reasonable control	Partial control	Partial control	Partial control	Contolled	Reasonable control	Reasonable control	Reasonable control
nicosulfuron + dicamba	2, 4	Post	Reasonable control	Reasonable control	Contolled	Reasonable control	Reasonable control	Reasonable control	Contolled	Reasonable control	Reasonable control	Contolled	Contolled	Reasonable control	Contolled	Reasonable control	Contolled	Reasonable control	Contolled	Contolled
nicosulfuron + atrazine	2, 5	Post																		
topramezone + atrazine	27, 5	Post	Contolled	Contolled	Contolled	Reasonable control	Reasonable control	Reasonable control	Contolled	Reasonable control	Contolled	Contolled	Contolled	Reasonable control	Reasonable control	Partial control	Contolled	Contolled	Contolled	Contolled
Split application																				
mesotrione > nicosulfuron	27, 2	Post	Reasonable control	Reasonable control	Contolled	Reasonable control	Partial control	Partial control	Contolled	Contolled	Reasonable control	Reasonable control	Reasonable control	Partial control	Partial control	Partial control	Contolled	Contolled	Contolled	Contolled
mesotrione > atrazine + nicosulfuron	27, 5, 2	Post	Contolled	Contolled	Contolled	Contolled	Contolled	Reasonable control	Contolled	Contolled	Contolled	Contolled	Contolled	Reasonable control	Reasonable control	Reasonable control	Contolled	Contolled	Contolled	Contolled
nicosulfuron > mesotrione	2, 27	Post	Partial control	Partial control	Partial control	Partial control	Partial control	Partial control	Reasonable control	Partial control				Reasonable control	Partial control		Partial control	Partial control	Partial control	Partial control
dicamba > nicosulfuron	4, 2	Post	Reasonable control	Contolled	Contolled	Contolled	Reasonable control	Reasonable control	Reasonable control	Partial control	Reasonable control	Reasonable control	Reasonable control	Reasonable control	Reasonable control	Partial control	Contolled	Contolled	Reasonable control	Contolled
fluthiacet-methyl > nicosulfuron	14, 2	Post	Not contolled	Partial control	Not contolled	Partial control	Not contolled	Not contolled	Reasonable control	Partial control	Not contolled	Partial control	Partial control	Not contolled	Partial control	Partial control	Reasonable control	Partial control	Reasonable control	Reasonable control
bromoxynil > nicosulfuro	6, 2	Post	Partial control	Partial control	Partial control	Partial control	Partial control	Partial control	Contolled	Partial control	Not contolled	Contolled	Contolled	Not contolled	Partial control	Partial control	Reasonable control	Reasonable control	Reasonable control	Reasonable control

Key: Contolled; Reasonable control; Partial control; Not contolled

* = not controlled if resistant populations exist.
Summer grass resisitant to nicosulfuron is common in Waikato and present in Bay of Plenty and Hawke's Bay.

7.5 Herbicide options for specific weeds

7.5.1 Perennial weeds

Perennial weeds can be spread by seed and/or vegetative material such as root fragments and bulbs (commonly spread by cultivation machinery). Remove all soil and plant material from cultivation equipment before entering cropping areas free of such weeds.

Successful control of perennial weeds may require a number of management strategies and take several seasons. Pre-emergence herbicides usually have little activity on perennial weeds; they are best managed with post-emergence herbicides or specific programmes (often using glyphosate or cultivation) after the crop has been harvested.

FAR and AgResearch trials have developed control strategies for the following perennial weeds.

Field bindweed (*Convolvulus arvensis*)
Field bindweed generally spreads from fence-lines first into the headland and then the main crop area. Maintaining control in fence-lines and headlands is a priority. Dicamba (Group 4) is the most effective post-emergence herbicide but generally is not 100% effective. Glyphosate (Group 9) may be applied with high clearance spray rigs in maize grain crops as they approach harvest, following black layer formation in the cob.

Oxalis (*Oxalis species*)
No agrichemical is fully effective at controlling oxalis. At the FAR arable site in the Waikato an established oxalis population was reduced from a 90% infestation to 5% over a five year period through a targeted strategy. This involved applying post-emergence sprays of mesotrione (Group 27) including terbuthylazine (Group 5) + Synoil™ in the mix) and nicosulfuron (Group 2) in alternate years. It is important to alternate the herbicides to prevent herbicide resistance developing in grass weeds. A post-harvest clean-up spray with glyphosate (Group 9) can be useful if the oxalis still has green leaves.

Docks (*Rumex species*) and buttercup (*Ranunculus repens*)
Use pre-cultivation and pre-plant clean up spray mixtures of glyphosate (Group 9) and thifensulfuron-methyl (Group 2) (e.g. Harmony) for killing docks and buttercups. Maize planting must be delayed for at least 14 days after treatment. Nicosulfuron (Group 2) has some activity against docks.

Couch / twitch (*Elytrigia repens*)
Nicosulfuron Group 2 has good activity against couch but follow-up applications are often required to treat late emerging plants. Post-harvest clean-up sprays with glyphosate (Group 9) can be useful where the weed still has green leaf.

Mercer grass (Paspalum distichum) and kikuyu (*Cenchrus clandestinus* syn. *Pennisetum clandestinum*)
As for couch, only a higher rate is recommended and treatment over at least two years will be required.

Californian thistle (*Cirsium arvense*)
Nicosulfuron (Group 2), dicamba and clopyralid (both Group 4) effectively control this weed in maize.

Indian doab (*Cynodon dactylon*)
Indian doab is the most difficult perennial weed to control in maize. It is tolerant to high rates of glyphosate Group 9 and nicosulfuron Group 2. Paraquat (Group 22) simply burns off the foliage for a short time. This weed is best managed by using harrows to drag the old stolons to the side of the field where they can be manually removed and destroyed. More research is required to develop successful control strategies for Indian doab.

Purple and yellow nutgrass (*Cyperus rotundus* and *Cyperus esculentus*)
Herbicides are only partially effective, and the best post-emergence option is halosulfuron-methyl (Group 2) (Sempra®). Clean up post-harvest applications of glyphosate (Group 9) can be used if there is sufficient green leaf remaining on the nutgrass plants. A winter crop of oats or similar may reduce the incidence of these weeds in the following maize crop.

7.5.2 Annual weeds

Black nightshade (*Solanum nigrum*)
Black nightshade is a summer annual, dying off with frosts in late autumn. It is generally controlled by cultivation and most herbicides, however it is resistant to some sulfonylurea herbicides, including metsulfuron (Group 2). It is not controlled by trifluralin (Group 3). Black nightshade populations known to be resistant to triazine herbicides such as atrazine (Group 5) have been identified in New Zealand. In maize, dicamba (Group 4) can be used to kill resistant plants.

Willow weed (*Persicaria maculosa*)
Willow weed is a summer annual, dying off in late autumn. In bare areas willow weed will scramble along the ground, but it will grow upright within crops and other vegetation. Although it likes moist soils, willow weed also needs soil to be well-aerated for optimal growth. Willow weed is susceptible to cultivation and most herbicides. However, some herbicides such as 2,4-D amine (Group 4), clopyralid (Group 4) and acetochlor (Group 15) only suppress, and do not kill willow weed. In some areas where atrazine (Group 5) has been applied for many years in succession, willow weed resistant to atrazine and other triazines has evolved. Such resistant plants can currently be managed in maize with mesotrione (Group 27), dicamba (Group 4) and nicosulfuron (Group 2).

Fathen (*Chenopodium album*)
Fathen is one of the most competitive cropping weeds in New Zealand. It is a summer annual, germinating from spring to early summer (but mostly in mid-spring), producing seeds over summer and autumn, and dying off with the first frosts in late autumn. It is generally controlled by most herbicide. However, fathen resistant to atrazine (Group 4) and some other commonly used herbicides from the triazine family (Group 5) has evolved in the Waikato and some other areas. Herbicides, including mesotrione (Group 27), topramezone (Group 27) and saflufenacil (Group 14) are currently able to control fathen with atrazine and dicamba (Group 4) resistance in maize.

Twin cress (*Lepidium didymium*)
Twin cress is an annual weed that can germinate at any time of year, though it establishes mainly in spring and autumn. It initially forms a small rosette, but as it grows it can scramble over other plants. It is generally not a large problem in maize. Where it does occur in maize it is controlled well by a range

of broadleaf herbicides, such as nicosulfuron (Group 2) used post-emergence and acetochlor (Group 15) used pre-emergence.

Shepherd's purse (*Capsella bursa-pastoris*)
Shepherd's purse is a fairly small annual weed that can germinate at most times of the year and is common in crops throughout New Zealand. It can complete its life cycle very quickly, so can undergo several generations a year. Shepherd's purse tolerates quite a few different herbicides, including selective herbicides such as dicamba, clopyralid and picloram (all Group 4)and trifluralin (Group 3). Pre-emergence herbicides such as acetochlor Group 15 and terbuthylazine Group 5 provide control, while flumetsulam (Group 2) and metribuzin (Group 5) can control seedlings post-emergence.

Thorn apple (*Datura stramonium*)
Thorn apple is an upright annual weed that grows up to 2m tall. It has a foul smell and produces flowers from spring to autumn. Herbicides for thorn apple in maize include atrazine (Group 4), dicamba (Group 4) and nicosulfuron (Group 2).

Summer grass (*Digitaria sanguinalis*)
Summer grass is a warm-temperature (C4) annual grass weed that, as the name suggests, grows mostly over summer, usually dying off with the first autumn frosts. Herbicides for summer grass in maize including acetochlor (Group 15), atrazine (Group 5) and nicosulfuron (Group 2). A few cases of nicosulfuron (Group 2) resistant summer grass have been found in the North Island.

Smooth witchgrass (*Panicum dichotomiflorum*)
Smooth witchgrass is an annual grass weed that is common in North Island maize crops, growing up to 1m tall. Like other C4 grasses, it is well controlled by herbicides such as acetochlor (Group 15) and nicosulfuron (Group 2).

Barnyard grass (*Echinochloa crus-galli*)
Another summer-active grass, barnyard grass is an annual weed that is common in North Island arable systems. This weed can build up in numbers when maize is continually cropped. Standard herbicide pre- and post-emergence programmes in maize are usually adequate to control barnyard grass.

Rough bristle grass (*Setaria verticillata*)
Rough bristle grass, also known as bristly foxtail, is a C4 summer-active grass that can be quite aggressive, due to its ready dispersal from its sticky seeds and seed heads. It is susceptible to most herbicides used to control other C4 grasses, such as acetochlor (Group 15), dimethenamid-P (Group 15) and nicosulfuron (Group 2).

Crowfoot grass (*Eleusine indica*)
Crowfoot grass (also known as goose grass) is another summer-active C4 grass. It is a tufted annual grass that can grow up to 40 cm high. Control as for other summer-active grasses.

Annual ryegrass (*Lolium multiflorum*)
Annual ryegrass, while an important cultivated crop and a part of many New Zealand maize-growing systems, can become a very troublesome weed in maize, significantly reducing yield if uncontrolled. Weed surveys in the North Island in recent years have found herbicide-resistant ryegrass in low numbers, but not in maize crops. Pre-emergence herbicides such as propachlor (Group 15) and terbuthylazine (Group 5) provide some control.

7.5.3 The role of adjuvants

Adjuvants include any substance added to the spray tank to change the physical properties of the spray mixture and the performance of the herbicide. They include stickers, surfactants (wetters and spreaders), penetrants, oils and water conditioners.

Surfactants work by reducing the surface tension of the spray solution, enabling the spray droplets to spread beyond their initial contact area. Increased coverage gives better herbicide absorption.

Stickers are materials that increase the chance that the spray droplets will stick to the leaf surface rather than bouncing off. Stickers are often water-soluble polymers, acrylic latex or resins. Wetting or spreading agents are often combined with stickers to improve coverage. These may also make the herbicide more rain resistant.

Some adjuvants increase the drying time for spray droplet, these are called humectants. Some work by drawing water from the atmosphere, others are oil-based. Herbicide absorption into the leaf only occurs when the herbicide is in solution, a slower drying rate enables more absorption.

Penetrants increase the movement of the herbicides into the leaf cuticle by softening or dissolving cuticular waxes. Some penetrants work by reducing the viscosity of the water carrier to a point where it can enter a leaf though the stomata (microscopic breathing holes in the leaf).

All herbicide products include adjuvants in their formulation, which control the performance of the herbicide. These products have been formulated to deliver the best result for the herbicide under the recommended label rates. The efficacy of the herbicide may be reduced if the label herbicide rate (g or mL/L) and water rate (L/ha) are not adhered to. Some adjuvants may reduce application rate and/or spray pattern which could lead to reduced herbicide efficacy and/or uncontrolled strips.

In addition, some herbicide products need a separate adjuvant combined with the herbicide at the time of mixing / application. Information about the correct adjuvant(s) and its application rate(s) is provided on the herbicide label. The choice of adjuvant is important; it must be compatible with both the herbicide and the target weed. The wrong adjuvant increases the risk of poor performance and crop injury.

Always check label recommendations and the manufacturer's recommendations about the most suitable adjuvant for mixing with a particular product. To prevent foaming, add adjuvants last when mixing spray products.

7.6 Mechanical weed management in maize

Key points:

- Maize is one of the easiest crops to weed mechanically - and get exceptional results.
- Mechanical weeding is best used in cultivated crops.
- The ideal weather window for mechanical weeding contrasts with herbicide spraying making the two highly complementary and supportive of each other.
- There are two main forms of mechanical weeders; contiguous that weed the whole field surface and incontiguous weeders that have gaps for the crop rows.
- Contiguous weeders for maize include the spring tine harrow, spoon weeder and the Einböck Aerostar-Rotation. They are a straight drop-in replacement for a herbicide application.
- Row-hoes are the primary incontiguous weeder. Modern row-hoes weed both interrow and intrarow using a diverse range of tools. They are more aggressive than contiguous weeders and require the drill and row-hoe to be perfectly matched.

7.6.1 Introduction

Mechanical weeding has improved almost immeasurably in the last few decades. The weeders have increased in size, flexibility and speed of operation, but, the biggest improvements are the automatic guidance systems for 'row-hoes'. With the increased use of mechanical weeding, particularly in Europe, mainstream agricultural machinery manufacturers are now selling turn-key solutions. Mechanical weeding in maize crops is increasingly important.

Unfortunately, it is rare for one mechanical weeding tool to provide complete weed control. Mechanical weeders must therefore be used as part of an overall integrated weed management package, which may still include herbicides. Intelligent integration of mechanical weeding and herbicides can give the best of both worlds.

Most mechanical weeders need cultivated soil to work and are unable to cope with large amounts of crop residue. Mechanical weeding is therefore incompatible with no-till (direct drilling). It may work in min-till, but this will depend on the amount of residue and the individual machines. Purpose designed high-residue row-hoes and spoon weeders cope with residue by design.

The effectiveness of most mechanical weeders is highest in hot, dry, windy conditions which desiccate the hoed weeds. They are less effective in cool wet conditions. This contrasts with herbicide application where hot, dry and windy conditions prevent application. Mechanical and chemical weeding therefore have contrasting application windows. Where both options are available this can considerably increase the overall weeding window - if it's hot and windy a mechanical weeder can be used, while in cooler still conditions herbicides can be used.

Maize is one of the easiest crops to mechanically weed and exceptional levels of mechanical weed control can be achieved. It is typically grown in wide rows, ideal for row-hoes, and is a tough robust and fast growing plant which can stand up to contiguous weeders. Also, it is often sown later in the season avoiding the cooler wetter conditions of early spring where mechanical weeding is less effective. This section gives a brief overview of mechanical weeding options in maize with links to further resources.

7.6.2 In-crop weeder types

In crop weeders are divided into two main types: Contiguous and incontiguous.

Contiguous weeders are also called 'broad acre' weeders. They are contiguous because they weed the whole field surface both crop and weeds at the same time. The main contiguous weeders are the spring tine harrow, the spoon weeder and the Einböck Aerostar-Rotation.

Contiguous weeders can be an alternative for boom applied herbicides, which are also applied contiguously. No other changes to the farm system are required. Do not use contiguous weeders after a pre-emergent herbicide which relies on a cap or skin of undisturbed soil to work, as mechanical weeding will break the cap and render the herbicide ineffective.

As contiguous weeders are applied to both crop and weeds it means the crop has to withstand the weeding action while the weeds need to be susceptible. As a large seeded, deeper sown, strong , quick growing crop, maize is able to withstand the weeding action, while most weeds in annual crops are small so they are susceptible.

Incontiguous weeders are typified by what were called interrow-hoes. However, these machines no longer just weed the interrow, they also weed the intrarow. They are thus increasingly called 'row-hoes' or row-crop-hoes'. Having different weeding tools in the interrow and intrarow gives considerable flexibility. Highly aggressive tools can be used in the interrow achieving very high levels of weed control, even with bigger weeds, while intrarow tools can be matched to weeds and the crop's growth stage, achieving weed control with minimal crop harm.

A key consideration with incontiguous weeders is that the hoe and the drill need to match, i.e., the spacing of the drill coulters needs to be exactly the same as the gaps in the hoe. The coulter spacing also needs to be exactly symmetrical so the hoe does not always have to follow the drill direction. In practice this means having dedicated pairs of drills and hoes set up the same. Unlike contiguous weeders, row-hoes are not a drop in replacement for herbicides. However, for larger areas, the flexibility of a row hoe can offset the additional complexity.

Computer guidance systems have solved what used to be one of the biggest challenges for row-hoes...accurately steering them. Computer guidance systems are mostly based on cameras, although a few use RTK-GPS systems. Guidance systems are now a mature technology with multiple providers; many row-hoes and guidance systems are sold as a single package. There are pros and cons for each, and large operators often have both. Get expert advice, FAR can help.

The many little hammer metaphor highlights there is not an either / or option between contiguous and incontiguous weeders. Typically, organic growers who cannot use herbicides and completely rely on mechanical weeding have both, possibly more than one type of weeder within each class. This is akin to having different types of herbicide, e.g., pre- and post-emergence, selective, broad spectrum etc. Clearly there a considerable costs in buying multiple weeders, but, where there are significant weed challenges, and/or larger areas of crop, the extra flexibility of multiple weeders will pay off. Contractors could be well placed to provide mechanical weeding as a service.

7.6.3 Spring tine harrows

Spring tine weeders go by a range of names including spring tine weeders, weeding harrows and occasionally finger weeders.

Spring tine harrows are the dominant form of contiguous weeder, especially in arable crops, and are the best entry into mechanical weeding. Developed over 50 years ago, there are many manufacturers. These weeders are based on flexible steel rods, around 5 mm in diameter that 'comb' through the soil surface breaking and burying weeds (Figure 28).

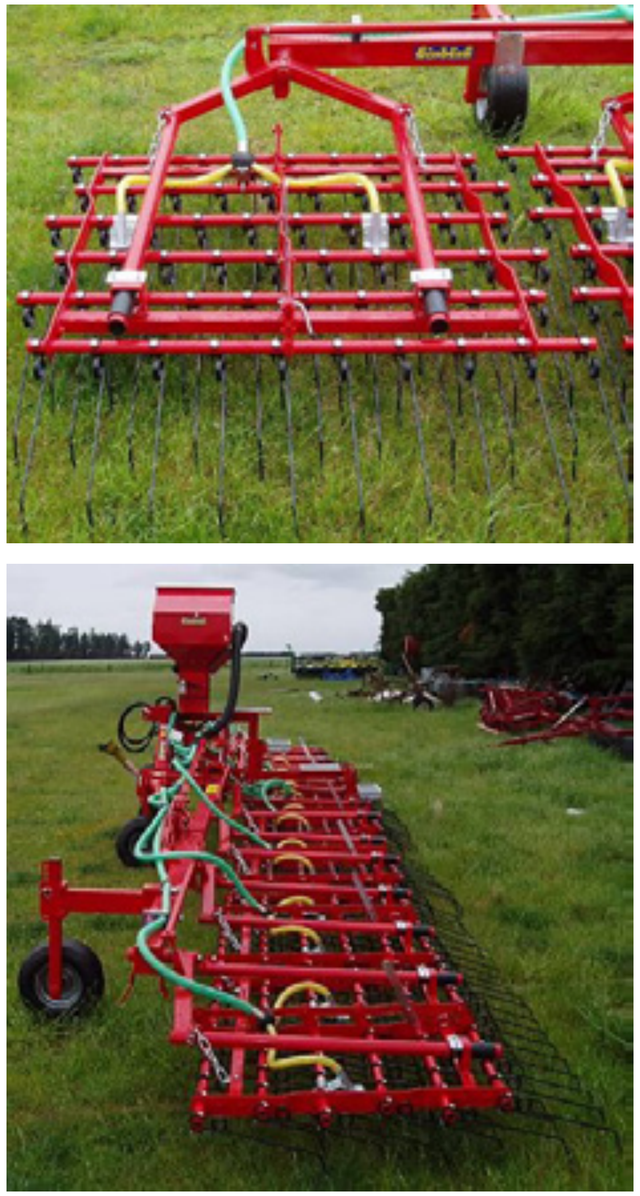

Figure 28. Spring tine weeder with pneumatic seeder.

Some machines can also integrate a pneumatic seeder, allowing them to be used for sowing cash crops, cover crops and pastures, as well as weeding. Their weeding action can be adjusted from very delicate to sufficiently aggressive to be used for cultivation / tillage.

7.6.4 Spoon weeder

Spoon weeders are known as rotary hoes in North America where they were invented and are more common. They consist of multiple spoked wheels with the ends of the spokes flattened into a spoon shape and angled, so that they enter the soil nearly vertically, and exit more horizontally, thus picking up a small amount of soil and flinging it into the air (Figure 29).

While originating in America, an increasing number of European manufacturers also produce spoon weeders with a range of improvements, e.g., better depth control. Spoon weeders directly impact less of the soil surface than spring tine weeders. As such, they rely on the soil thrown in the air to break and bury weeds as it lands. For this reason, they only effectively kill cotyledon stage weeds. Conversely, spoon weeders are highly effective at breaking soil caps and will work in soil that is too hard for a spring tine weeder. High residue designs are also available (Figure 29).

Figure 29. Top, high residue original North American spoon weeder (rotary hoe); below, new European design (Einböck GmbH).

Einböck Aerostar-Rotation

The Aerostar-Rotation is a proprietary design unique to Einböck. It consists of multiple spoked wheels, but, unlike the spoon weeder, the spokes are simple round steel rods, and the wheels are angled to the direction of travel forcing the spokes to scuff through the soil. It's weeding action is therefore more like the spring tine harrow than a spoon weeder. However, the Aerostar-Rotation is considerably more aggressive than a spring tine harrow and maize plants will be damaged if it not used carefully. It should be viewed as complimentary to a tine or spoon weeder, to be called upon in more challenging conditions and where weeds have grown larger. It is also not recommended for those new to mechanical weeding.

Figure 30. Einböck Aerostar-Rotation. Photos Einböck GmbH.

7.6.4.1 Row-hoes

Modern row-hoes are very different from their interrow ancestors. While there are now many dozens of manufacturers, the design of modern hoes has converged to multiple independent parallelogram units (Figure 31). The parallelogram units carry the toolframe which ensures that the toolframe is kept parallel to the ground and at the correct height. The toolframe in turn carries the weeding tools. Toolframes vary from 15 cm to about 1 metre wide. The parallelogram units are mounted onto a toolbar with a three point linkage attachment. This allows machines to be very wide e.g., >25 metres.

Figure 31. Roe-hoe consisting of a number of independent parallelogram units mounted on a toolbar. Right photo Garford Farm Machinery Ltd.

While interrow hoes only weed the interrow, there are a growing number of intrarow weeding tools that can be mounted on row-hoes, hence the change of name as they weed both interrow and intrarow. The row-hoe is thus not so much a weeder, as a platform on which a highly diverse range of weeding tools can be mounted. They can weed delicate crops, such as carrots as well as robust crops like maize. The wide rows of many maize crops are also ideal for row-hoes, as the majority of the paddock is interrow which can be aggressively weeded, and quick growing large and robust maize plants are effective in-row competitors with weeds and stand up to intrarow weeding tools very well.

Interrow weeding tools are commonly based around horizontal knife blades which have an aggressive weeding actions that can cut through larger weeds, including perennials like Californian thistle and docks.

The main intrarow tools are mini-ridgers, rotating wire weeders and finger weeders. While there are a number of other intrarow weeder designs, they are often obscure or not relevant for maize.

Mini-ridgers are a simple but exceptionally effective tool. They create a precisely sized, small soil ridge in the crop row burying the weeds but leaving the crop sticking out of the soil ridge. This can achieve 100% weed control, even in cool and wet conditions. See https://merfield.com/research/2018/mini-ridgers--lethal-burial-depths-for-controlling-intrarow-weeds-2018-ffc-merfield.pdf for detailed information.

Rotating wire weeders are equally simple. They consist of thin rod tines placed around the outside of a 'wheel' on an offset angle (Figure 32).

The offset angle causes the wheel to rotate and scuff the tines through the crop row. They are very effective in upright crops such as maize.

Finger weeders are the most common intrarow weeder with many different manufacturers. They consist of two star-like disks of fingers, one pushes through the crop row, the other digs into the soil making the weeder rotate (Figure 33).

These three tools are complimentary. Pairing the mini-ridger with either a wire or finger weeder allows the mini-ridger to be pulled up and then pulled down, the same as potato ridges. The finger and wire weeders rotate in different planes, so alternating between the two can kill more weeds.

See https://merfield.com/research/2014/the-final-frontier--non-chemical,-intrarow,-weed-control-for-annual-crops-with-a-focus-on-mini-ridgers-ffc-bulletin-2014-v4-merfield.pdf for more information on intrarow weeders.

7.6.5 Interrow hoeing and band sprayed herbicides

Using a row-hoe to weed the interrow area and then band spraying pre-emergence herbicides down the intrarow can be a powerful integrated weed management technique. The aggressive interrow weeding tools can achieve very high levels of weed control between the crop rows. Herbicides can then achieve good weed control within the crop row, where mechanical weeding can be less effective. This reduces the total amount of herbicides used, helping slow he development of resistance by reducing the number of weeds herbicides are applied to. It may also allow more expensive, but effective herbicides, to be used, as they are applied to a much smaller area of the paddock.

7.6.6 Further information

FAR Arable Extra 134 Extra 134 Mechanical weed management https://www.far.org.nz/resources/extra-134-mechanical-weed-management

Manage Weeds On Your Farm: A Guide to Ecological Strategies SARE https://www.sare.org/resources/manage-weeds-on-your-farm/

An Integrated Weed Management framework: A pan-European perspective https://www.sciencedirect.com/science/article/pii/S1161030121002148

Weed Biology and Weed Management in Organic Farming https://www.intechopen.com/chapters/25094

MSU Mechanical Weed Control YouTube channel https://www.youtube.com/channel/UCH-k889oYbUaEznvgiDtrOQ

Figure 32. Rotating wire weeder. Photo Steketee.com.

Figure 33. Finger weeders.

8. IWM - Reduce weed seed return

The final stage of the IWM weed life cycle approach is reducing weed seed return. Every seed kept out of the weed seedbank is a future weed that cannot exist - hence the old farming adage, "one year's seeding - seven years weeding". The adage may be overly pessimistic at seven years, three to four would be closer to the mark, but, it does emphasise that one of the most effective ways to manage weeds is to stop seed shed.

8.1 Stubble management, tillage, mowing, grazing and post-harvest herbicides

Post-harvest stubble management can have a large weed management impact in arable crops. However, maize-specific research, particularly in New Zealand, is limited. However, for arable crops in general, seeds in stubble and on the soil surface will be eaten by a wide range of seed eaters such as birds and beetles. Allowing time between harvest and cultivation, especially ploughing, may allow more seed predation.

As discussed in Section 7, tillage can play an important role in managing shed seed.

IWM options for controlling weeds that survive harvest and continue to grow and produce seed include mowing, grazing and post-harvest herbicides. There are pros and cons for all approaches, and limited research specifically in maize in New Zealand.

Mowing is a simple and effective way of stopping many weeds from continuing to produce seeds, and even kill them, but it is energy intensive, especially in maize grain crops with large amounts of stover, so can be costly in terms of diesel used.

Many annual crop weeds are palatable, even nutritious to stock, so they will readily graze them. However, other weeds may be harmful, or even toxic. Check weed species resent before using livestock to clean up paddocks. Get advice and or check on online databases, e.g. poisonousplants.ansci.cornell.edu. Grass seeds tend to be killed when eaten by livestock, but due to their hard seed coats, many broadleafs will survive digestion, or even have dormancy removed, increasing their immediate germination rates.

Herbicides are the final alternative to control seeding weeds post-harvest. Stick to the farm's overall herbicide resistance management strategy and choose a herbicide from a group, that has low resistance risk. Even systemic herbicides are unlikely to kill seeds that have already formed on the plant, and particularly those that are mature when herbicides are applied. The aim is to stop them producing any more seeds.

8.2 Clean machinery

Machinery is a key route for transferring weed seeds and plant propagules, as well as pests and diseases across and between farms. Harvesters are a particularly risk as they are working in the crop at the time when viable weed seeds are being shed, and, they have a lot of places where seeds can accumulate. In a perfect world, all machinery moving between paddocks or properties with different weed problems would be fully cleaned down. Unfortunately, in the busy harvest season machinery clean down may not be a priority. However, it is increasingly important to 'triage' machinery moving between locations, to determine if it has come from a high risk location with known herbicide resistance, biosecurity issues or other issues that could impact your farm business. Ongoing conversations between growers and contractors are needed, and growers using the same contractor need to be talking to each other about the weed challenges their equipment could be spreading. Clean down requirements may need to be built into contracts in future.

8.3 Harvest weed seed control (HWSC)

Harvest weed seed control (HWSC) is a rapidly expanding technique for killing or manipulating weed seeds moving through the harvester / header / combine. It originated in Australian cereal crops and is based on separating the straw from the chaff, which contains nearly all the weed seed. Then numerous techniques are used to destroy or capture the weed seed, stopping it returning to the weed seed bank. See www.weedsmart.org.au/content/harvest-weed-seed-control-in-a-nutshell/ for an introduction to HWSC.

While HWSC is proving highly effective in its native Australia, and is now spreading to North America and Europe, and is being tested in cereals by FAR in New Zealand. Its viability in maize crops, both silage and grain, is untested here, although some work is beginning in US maize (corn). There are a number of factors that are likely to limit its use, particularly the very high biomass of maize, so it is currently considered a non-starter in New Zealand maize. Although this could change with new technology.

8.4 Scouting and roguing

Where herbicide resistance is known, or suspected and/or biosecurity weeds are or could be present, then post-harvest paddock scouting and manually roguing or spot spraying weeds can pay considerable dividends in minimising seed shed. This may include removing plants with seeds from the fields making sure seeds are not lost during the process (e.g. put into plastic bags, or bins without any drain holes in them). The plants should then be dealt with so the seed cannot find its way back onto any paddocks, e.g. landfill or burnt.

9. Overall conclusions

Herbicide resistance and biosecurity challenges have increased the complexity of weed management over the last decade. These issues are compounded by the loss of existing products, a lack of new herbicide products and groups, and New Zealand's difficult agrichemical product registration system. To address these challenges the international weed science community has developed the concept of integrated weed management (IWM) bringing all the weed management tools together. IWM provides an increasing range of options and foremost among these are mechanical weeders, which are now a fully mature technology with turn-key offerings from many manufacturers including some of the world's largest agricultural machinery companies. Mechanical weeders are becoming the new normal in places such as Europe and New Zealand growers are well placed to take advantage of these advances and integrate mechanical weeding into their maize production systems.

10. Further resources

- Grass Weeds of Arable Crops – The Ute Guide. Trevor James. www.far.org.nz/resources/grass-weeds-of-arable-crops-ute-guide
- Broadleaf Weeds of Arable Crops – The Ute Guide. Trevor James. www.far.org.nz/resources/broadleaf-weeds-of-arable-crops-ute-guide
- Yellow Bristle Grass – The Ute Guide. Trevor James. www.far.org.nz/resources/yellow-bristle-grass-identification-ute-guide

11. Acknowledgements

11.1 First edition - Weed Management in Maize

Authors

Diana Mathers	FAR
Mike Parker	FAR
Trevor James	AgResearch

Science providers

Trevor James	AgResearch
Anis Rahman	AgResearch
Mike Trolove	AgResearch
Claire Dowsett	AgResearch

Photos

Mike Parker	FAR
Diana Mathers	FAR
Trevor James	AgResearch

Funders

FAR
MPI Sustainable Farming Fund

11.2 Second edition - Maize Integrated Weed Management

Authors

Charles Merfield	FAR
Abie Horrocks	FAR
Andrew Pitman	FAR
David Densley	FAR
Dirk Wallace	FAR
Matilda Gunnarsson	FAR
Sam McDougall	FAR
Steven Payne	FAR

Editor

Anna Heslop	FAR

Science advisors

Trevor James	AgResearch

Photos

Trevor James	AgResearch

Graphic design

Melissa Hillmer	Blueprint

Funders

FAR
M.B.I.E.