PART III – PROTECTING THE CROP

A cloud over pesticide use (Courtesy: Michael Walsh)

Crown rot in wheat becomes a challenge in stubble retained systems (Courtesy: Steven Simpfendorfer)

Herbicide resistant ryegrass in lupins at Wagga Wagga, 1988 (Courtesy: Jim Pratley)

First recorded case of glyphosate resistance (1995): in annual ryegrass from a farm at Echuca, Victoria (Courtesy: Jim Pratley)

Chapter 10

Weed control in cropping systems – past lessons and future opportunities

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The weed control environment

Weed control in Australian crops has been through a revolution over the last three decades, transforming from a dependency on cultivation, with associated soil degradation issues, to herbicide reliance in conservation agriculture (CA) systems. The resulting dramatic change in the crop production environment has resulted in a similarly significant impact on weed control practices. The adoption of CA is underpinned by the availability of highly efficient, selective herbicides, but the absence of alternate weed control technologies has led to an overreliance on herbicides. The widespread evolution of herbicide resistance now threatens the sustainability of CA systems (Powles and Yu 2010).

Australian farmers, like those elsewhere, are continually confronted by weeds that impact crop yields, quality and profitability (Oerke 2006). A study by Llewellyn *et al*. (2016) determined that the cost of weeds to Australian grain growers was $3.3 billion per year due to a combination of lost production ($0.75 billion) and weed control expenditure ($2.57 billion). Herbicide resistance is already a significant component of weed control costs ($187 million) and with no new herbicides in the foreseeable future this cost will continue to escalate (Llewellyn *et al.* 2016).

Historical perspective on weed control in cropping systems

Cropping systems and weed control prior to 1980s

The impact of weeds on crop yields has been a challenge since crop production began. Initially it was addressed by shifting agriculture from place to place and then, as implements became available, by cultivation practices to destroy weeds (Pratley and Rowell 1987). Some weeds, notably skeleton weed (*Chondrilla juncea*) readily adapted to this and fields were converted to pasture for a period to enable livestock to control weeds (Cuthbertson 1967, Wells 1970) – a stimulus for 'ley farming' in the 1930s.

Weed seed collection was a part of the harvest operation for years prior to 1987 and well before the introduction of the current harvest weed seed control (HWSC) technologies. Harvesting equipment used during this period allowed the collection of some weed seed as well as small and broken grain via the screening of grain as it entered the grain tank. This material, referred to as 'seconds' was subsequently collected in an additional storage tank. This technology was relatively effective in that the seconds were 'bagged-off' and fed to the farm poultry or otherwise disposed of. This capability became obsolete from the 1970s with changes in harvester threshing and cleaning systems that enabled increased processing efficiency, and therefore harvester capacity. Weed seeds, however, were dispersed with the chaff back onto the soil.

Cropping systems and weed control 1980s – 2020

The need to improve soil structure, retain nutrients and conserve soil moisture has driven the widespread adoption of conservation cropping practices based on reduced tillage and stubble retention (FAO 2015, Kassam *et al.* 2012, Llewellyn *et al.* 2012). The introduction and development of conservation cropping practices in Australia began in the 1970s and was initially based on the restricted use of cultivation prior to, and at seeding. During this period there was much experimenting with the use of 'knockdown' herbicides paraquat plus diquat (Spray.Seed®) and glyphosate. Adoption rates were initially low but rapidly increased through the 1990s as seeding implement technology developed and the benefits of this approach was realised. Subsequently, tillage operations were further restricted at seeding with knife-point fitted tynes or disc seeding systems.

During the first half of this period the availability of highly effective herbicides for pre-seeding weed control and selective in-crop weed control became a significant driver in the success of conservation cropping systems (D'Emden *et al.* 2008). The most important of these were acetyl coenzyme A carboxylase (ACCase) inhibitors, *e.g.* dichlofop methyl (Hoegrass®), and acetolactase synthase (ALS) inhibitors, *e.g.* chlorsulfuron (Glean ®), (Powles and Howat 1990) which for the first time provided highly effective control (up to 99%) of the dominant grass (annual ryegrass and wild oats) and broadleaf (wild radish) weeds. The success of these herbicides paved the way for a proliferation of in-crop selective herbicides that, in most cases, were highly effective, easy to use and readily adopted by farmers.

The adoption of CA has improved soil condition and structure as well as allowing more frequent and timely access to fields with farm equipment for crop planting, crop protection treatments and harvest. Crop planting delays due to wet soils were substantially reduced. More timely herbicide applications have increased efficacy by targeting weeds at their most vulnerable growth stage. Planting on time, or even early, provides for a more vigorous establishment with improved weed competition (see Chapter 18).

Prior to the adoption of CA, crop stubbles were usually burnt in autumn to remove residues for ease of sowing and to control stubble-borne diseases, pest and weeds. Stubble burning can reduce the viability of annual ryegrass seed present on the soil surface by 80%. Temperatures of burning stubbles are higher above the soil (20 cm) than at the surface reducing seed viability if the seed is retained in the seed head (Walsh and Newman 2007). The value of soil cover for erosion minimisation and soil moisture retention prompted delays in burning closer to sowing. Ultimately, burning was largely replaced by stubble retention with the introduction of seeding systems with stubble handling capability.

Herbicide resistance in Australian cropping systems

Before the 1970s/1980s herbicide revolution, tillage and, to a lesser extent, residue burning were the major methods of weed control in Australian cropping systems. The availability of the non-selective herbicides, paraquat/diquat and glyphosate, allowed efficient pre-seeding weed control (Matthews 2018) thereby reducing or removing the need for tillage (Pratley and Rowell 1987). The development of the ACCase and ALS inhibiting herbicides enabled highly effective in-crop weed control with little or no effect on crop growth and development (Matthews 2018). Their control of many grass weeds in cereal crops led to marked increases in herbicide use. The use of herbicides for pre- and post-seeding weed control removed the need for tillage and residue burning to control weeds, facilitating the development of CA.

The efficacy of herbicides has been integral to the success of CA but the subsequent overreliance has placed strong selection pressure on weed populations for resistance evolution. Through most of the 20th century, livestock production dominated the current cropping region and annual ryegrass (*Lolium rigidum*) pastures were established as a valuable source of forage. Thus, by the 1970s, when crop production and herbicide use intensified, annual ryegrass was well established in large, naturalised populations throughout the grain production regions (Donald 1965, Kloot 1983). While highly productive as a pasture species, annual ryegrass possesses the key attributes of a resistance-prone weed species (*i.e.* high genetic variability, obligate out-crossing, high seed production and rapid seed bank turnover) that has resulted in it becoming the world's most resistance-prone weed. The strong selection pressure imposed by the highly effective ACCase and ALS inhibiting herbicides on large populations of this species was a 'perfect recipe' for the widespread evolution of multi-resistant populations.

The first case of evolved herbicide resistance in Australia was reported in 1982 following just six applications of diclofop-methyl to an annual ryegrass population (Heap and Knight 1982). This population was also found to be cross resistant to a range of ACCase and ALS inhibiting herbicides (Heap and Knight 1986, 1990). Despite the clear warning of this first case of resistance, the message was largely ignored and within a relatively short period (5-10 years) the evolution of herbicide resistant weed populations began to impact on the viability of conservation cropping systems (Powles *et al.* 1997).

Table 1 Herbicide resistant weeds of Australian cropping (adapted from Heap 2019)

Species with evolved herbicide resistance	First reported	Herbicide family/site of action
Arctotheca calendula (capeweed)	1986	Synthetic auxins, PS1
Avena fatua (wild oats)	1985	ACCase
Avena ludoviciana (wild oats)	1989	ACCase, ALS, Unknown
Brachiaria eruciformis (sweet summer grass)	2014	EPSPS
Brassica tournefortii (wild turnip)	1992	ALS
Bromus diandrus (great brome)	1999	ACCase, ALS, EPSPS
Bromus rigidum (rigid brome)	2007	ACCase, ALS
Bromus rubens (red brome)	2014	EPSPS
Chloris truncata (windmill grass)	2010	EPSPS
Chloris virgate (feathertop Rhodes grass)	2015	EPSPS
Conyza bonariensis (flaxleaf fleabane)	2010	PS1, EPSPS
Conyza sumatrensis (tall fleabane)	2018	PS1
Cyperus difformis (small umbrella flower sedge)	1994	ALS
Damosonium minus (starfruit)	1994	ALS
Digitaria sanguinalis (large crab grass)	1993	ACCase, ALS
Diplotaxis tenuifolia (Lincoln weed)	2004	ALS
Echinochloa colona (awnless barnyard grass)	2004	PS11, EPSPS
Echium plantagineum (Paterson's curse)	1997	ALS
Eleusine indica (goosegrass)	2015	PS1
Erharta longiflora (annual veldt grass)	2014	ACCase
Fallopia convolvulus (climbing buckwheat)	1993	ALS
Fumaria densiflora (fumitory)	1999	Microtubule inhibitors
Galium tricornutum (three horn bedstraw)	2012	ALS
Gamochaeta pensylvanica (cudweed)	2015	PS1
Hordeum glaucum (wall barley grass)	1982	ACCase, ALS, PS1, EPSPS
Hordeum leporinum (barley grass)	1988	ACCase, PS1
Lactuca saligna (wild lettuce)	2017	EPSPS
Lactuca serriola (prickly lettuce)	1994	ALS, EPSPS
Lolium rigidum (annual ryegrass)	1982	ACCase, ALS, PS11, Microtubule inhibitors, Lipid synthesis inhibitors, VLCFA inhibitors, PS1, EPSPS, Carotenoid biosynthesis inhibitors (unknown target)
Mitracarpus hirtus (tropical girdlepod)	2007	PS1
Nassella trichotoma (serrated tussock)	2002	Lipid synthesis inhibitors
Pentzia suffruticosa (Calomba daisy)	2004	ALS
Phalaris minor (lesser canary grass)	2012	ACCase
Phalaris paradoxa (hood canary grass)	1997	ACCase, ALS
Poa annua (winter grass)	2009	ALS, PS11, Microtubule inhibitors, EPSPS, Unknown
Rapistrum rugosum (turnip weed)	1996	ALS
Raphinus raphanistrum (wild radish)	1997	ALS, PS11, PDS inhibitors, Synthetic auxins, EPSPS
Sagittaria montevidensis (arrowhead)	1994	ALS
Sinapis arvensis (wild mustard)	1996	ALS
Sisymbrium orientale (Indian hedge mustard)	1990	ALS, PS11, PDS inhibitors, Synthetic auxins
Sisymbrium thellungii (African turnip weed)	1996	ALS
Solanum nigrum (blackberry nightshade)	2015	PS1
Sonchus oleraceus (sow thistle)	1990	ALS, Synthetic auxins, EPSPS
Sporobolus fertilis (giant Parramatta grass)	2004	Lipid synthesis inhibitors
Tridax procumbens (tridax daisy)	2016	EPSPS
Urochloa panicoides (liverseed grass)	1996	PS11, EPSPS
Urtica urens (stinging nettle)	2002	PS11
Vulpia bromoides (silver grass)	1990	PS11, PS1

Herbicide-resistant weed populations have evolved throughout the world's cropping regions (Heap 2019), but multiple resistance evolution has been most extensive across the Australian grain production region (Table 1). Susceptibility in annual ryegrass populations is now rare with the predominant scenario being ACCase inhibiting and/or ALS inhibiting herbicide resistance (Owen *et al.* 2014, Boutsalis *et al.* 2012, Broster and Pratley 2006, 2019, Broster *et al.* 2013b, see Table 2). This weed has evolved resistance to eleven modes of action (MOA); ACCase inhibitors (Heap and Knight 1982), ALS inhibitors (Heap and Knight 1986), PSII inhibitors (Burnet *et al.* 1991), microtubule inhibitors (McAlister *et al.* 1995), mitosis inhibitors (Heap 2019), bleachers (Burnet *et al.* 1991), fat synthesis inhibitors (Brunton *et al.* 2018), VLFCA inhibitors (Heap 2019), PSI inhibitors (Heap 2019), EPSP synthase inhibitors (Pratley *et al.* 1996) and carotenoid biosynthesis inhibitors (Burnet *et al.* 1991). The frequency and distribution of multi-resistant annual ryegrass populations ensures that this species now dominates weed management decisions on the majority of Australian farms.

Table 2. Frequency of herbicide resistance in randomly collected annual ryegrass (*Lolium rigidum*) populations collected across Australia's crop production regions

Herbicide	**Herbicide family/ site of action**	**WA**	**NSW**	**SA**	**Vic**	**Tas**
Diclofop	ACCase	96	64	58	73	46
Sethoxdim	ACCase	79	-	-	-	-
Clethodim	ACCase	65	10	9	8	8
Chlorsulfuron	ALS	-	-	70	71	-
Sulfometuron	ALS	98	57	-	-	16
Imazamox/imazapyr	ALS	-	53	58	31	20
Trifluralin	VLCFA	27	9	57	8	8
Simazine	PSII	-	0	-	-	-
Atrazine	PSII	2	-	-	-	-
Glyphosate	EPSPS	7	3	3	2	0
Paraquat	PSI	0	-	-	-	-

Data from (Broster *et al.* 2013b; Owen *et al.* 2014) and J. Broster and P. Boutsalis pers. comm.
WA values are populations with ≥1% survival, NSW and Tasmania are for >10% survival and Vic and SA values are for ≥20% survival at recommended rate

– Indicates herbicide not used in screening.

The extent of herbicide resistance in other major weed species of Australian cropping (*e.g.* wild oats, wild radish, sowthistle, fleabane) is less severe than that of annual ryegrass, but significant, nonetheless. A 2010 survey of the WA wheatbelt found 71% of randomly collected wild oat populations were resistant to the ACCase inhibiting herbicide, diclofop-methyl (Owen *et al.* 2014, Owen and Powles 2016). Similar surveys of southern NSW identified 38% and 20% of wild oats were resistant to diclofop-methyl (Broster *et al*. 2011a, 2011b, 2013b). In WA over 80% of wild radish populations were resistant to sulfonylurea herbicides (Owen *et al.* 2015b) compared with 15% in NSW (J Broster unpublished data). In WA there are also significant frequencies of multi-resistant populations with 30% resistant to three MOA. Results from a survey in 2010 indicated that only 7% of randomly collected populations remained herbicide susceptible (Owen *et al.* 2015b). In southern NSW where sowthistle is more commonly found, over 50% of populations were resistant to sulfonylurea herbicides while glyphosate resistance is common in northern NSW (Broster *et al.* 2012, unpublished data, Jalaludin *et al.* 2018).
Resistance to multiple MOA has been reported for both brome grass and barley grass. In WA 13% of brome grass populations were reported to be resistant to sulfonylurea herbicides (Owen *et al.* 2015a). In the South Australian Mallee, western Victoria and western NSW, where brome grass is more prevalent, the extent of resistance was greater with resistance to the sulfonylurea herbicides in 45%, 37% and 28% of populations respectively (Boutsalis *et al.* 2014, J. Broster unpublished data). Barley grass resistance is lower with occasional populations resistant to ACCase and ALS inhibiting herbicides although paraquat resistant populations have been reported in both NSW and Tasmania, the majority being in established lucerne pastures (J Broster unpublished data).

The role of glyphosate and other herbicide tolerance traits

The growth of glyphosate resistance globally is of particular concern with over 40 species now confirmed with resistance to this herbicide (Preston 2019). Resistance was first identified in the late 1990s in Australian annual ryegrass populations (Pratley *et al.* 1996, Powles *et al.* 1998, Pratley *et al.* 1999). Since this initial discovery the frequency of glyphosate resistance in Australia has continued to increase (Broster *et al.* 2019, Preston 2019), while globally much of the growth in frequency of glyphosate resistant species (Figure 1) has occurred since the commercial availability of Roundup Ready™ crop varieties, notably in soybean, corn and cotton.

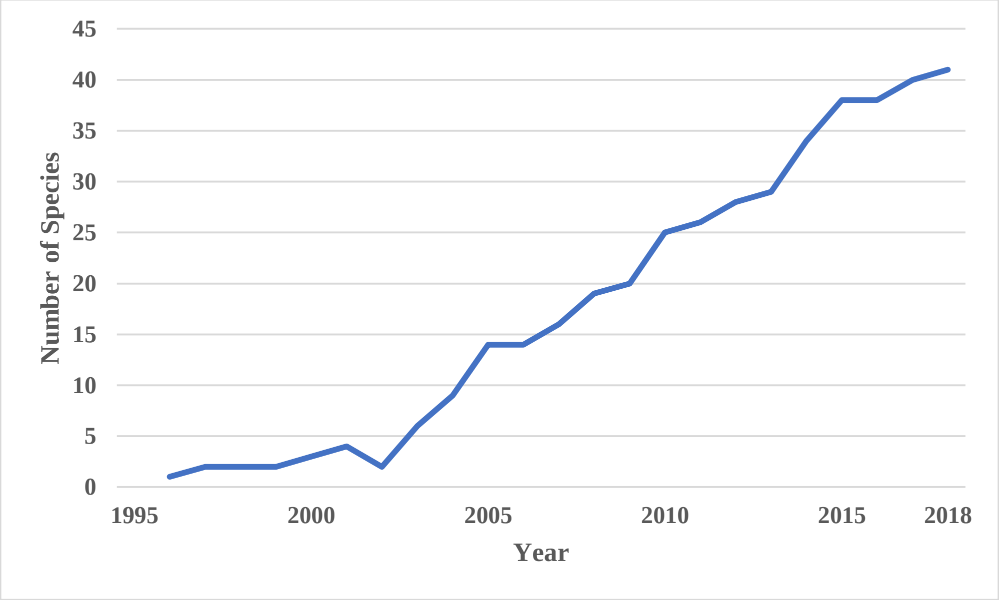

Figure 1. Increase in glyphosate resistant weeds globally, 1990 to 2015 (Heap 2019)

Glyphosate has been, and remains, fundamental to conservation cropping systems, globally. Recent technologies have increased dependency through the inclusion of glyphosate tolerance traits in some crops, notably canola in Australia. Glyphosate resistance traits are now the basis for the gene stacking approach where, in an attempt to combat herbicide resistance evolution, multiple herbicide resistance traits are being combined within single biotypes of some crops. This phenomenon of multiple herbicide-tolerances through gene stacking has been reviewed by Gressel *et al.* (2017). The use of glyphosate tolerance traits has dominated the development of herbicide tolerant crops and is now universally used when traits are stacked and has dramatically changed the use pattern of glyphosate from solely a knockdown herbicide (*i.e.* pre-planting seedbed vegetation control) to a broad-spectrum, in-crop selective herbicide. In doing so, it frequently is the last herbicide used in the growing season and so any survivors will contribute to resistance evolution. In Australia, to date, the glyphosate resistance traits have been confined to cotton (registered from 1996) and subsequently canola (registered from 2003 but grown only in NSW and Victoria since 2008 and in WA since 2010). The incidence of glyphosate resistance in Australia is shown in Figure 2 indicating its spread since 2005 across the southern cropping belt of Australia where canola is grown.

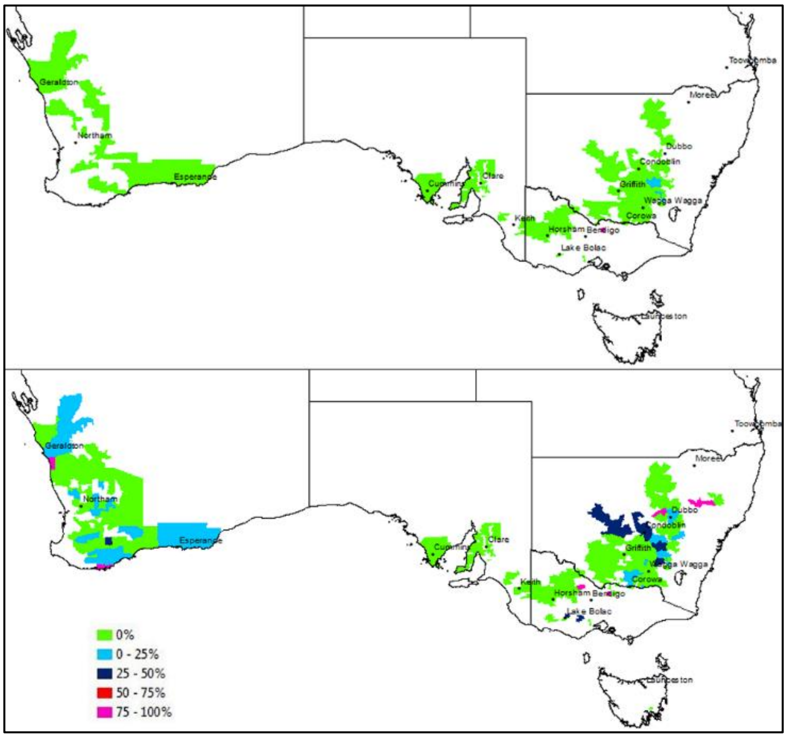

Figure 2. Increase in incidence of glyphosate resistance in the Australian southern cropping zone 2005 (top) to 2018 (bottom) (Broster *et al*. 2019)

Weed control environment of conservation cropping systems

Crop establishment and residual herbicides The widespread adoption of CA incorporating minimal cultivation and stubble retention (Llewellyn *et al.* 2012) has many benefits including soil cover and reduced moisture loss but provides some challenges in weed control measures (Figure 3). The retention of residues creates an artificial emergence depth for crop seedlings that requires extended hypocotyls *e.g*. canola (Bruce *et al.* 2006b) and the micro-environment can be 2-3 ^{0}C colder in winter, both of which can reduce the vigour of emerging crop seedlings relative to that of the competing weeds (Bruce *et al.* 2006a).

Figure 3. The presence of cereal stubble interfering with the capability of canola seedlings to establish at Harden NSW (Bruce *et al.* 2006c)

Crop residues act as a physical barrier and can intercept and absorb a large proportion of soil active herbicides which reduces the quantity reaching the soil surface and can compromise the efficacy on weed populations (Banks and Robinson 1982, Chauhan *et al.* 2006c). This absorbed herbicide may also be released later from the degrading stubbles to impact on subsequent susceptible crops (*e.g.* Pratley 1992).

A seedbank focus for annual weed control The impact of weeds on crops is largely a function of numbers – depleting the seedbank is an obvious management tactic to restrict crop weed infestations (Buhler *et al.* 1997). While the methods by which farmers address the weed challenge have evolved in conjunction with the adoption of CA, the dominant weeds of Australian cropping systems are annual species that are reliant on a viable seedbank for persistence and interference in annual cropping systems. Similar to the approaches used in previous, less conservative systems, weed management programs in conservation cropping systems remain focussed on practices aimed at depleting weed seedbanks. In general, seedbanks are depleted by minimising recruitment and by encouraging seedbank decline. Alternatively, some weed species can be encouraged to germinate by a light cultivation of the surface soil. In winter crops, annual ryegrass and fumitory respond in this way enabling control through a follow-up herbicide or further cultivation at the seedling stage prior to sowing. In CA, cultivation has been discouraged but occasional strategic tillage may be helpful (see Chapter 7)

Impact of reduced tillage In NT systems, most weed seeds remain on or near the soil surface after crop planting. Vertical weed seed distribution in these systems is mainly influenced by sowing depth and the type of sowing points. In a southern Australian study, a NT system retained 56% of annual ryegrass seeds in the top 1 cm soil layer, whereas only 5% seeds were found in this layer in a CT system (Chauhan *et al.* 2006b). The adaptation to NT also changed the weed spectrum with Paterson's curse (*Echium plantagineum*) and *Vulpia* spp. (Forcella 1984) apparently better adapted to the lack of soil disturbance, but fumitory and to some extent annual ryegrass (Pratley 1995) for a time were less-well adapted. The differential seed distribution in the soil profile can affect weed population dynamics by affecting soil temperature, soil moisture, light conditions and predator activity (Buhler 1997). Seeds present on or near the soil surface are prone to predation and rapid decay due to unfavourable weather conditions (Mohler 1993). Higher levels of decay have been reported for seeds present on the soil surface compared with buried seeds (Chauhan *et al.* 2006a), suggesting CA systems provide the opportunity to deplete the seed bank more rapidly.

CT systems favour larger-seeded weed species that can emerge from depths of >5 cm, while small-seeded species are favoured by NT as more seeds are at or near the soil surface. Some of the favoured weed species are African turnip weed, common sowthistle, feathertop Rhodes grass, flaxleaf fleabane, Indian hedge mustard and windmill grass. Small-seeded species commonly have a light requirement for germination and so those seeds present on the soil surface in NT systems are prone to germination in response to the break in the season. Where available, a light irrigation could be used to stimulate weed seed germination. Emerged seedlings can then be killed using a non-selective herbicide prior to crop planting. Hard-seeded species, such as marshmallow and bladder ketmia, generally require scarification to germinate. These species have an impermeable seed coat, which increases their persistence if buried in the soil. In NT systems, seeds present on the soil surface experience fluctuating temperature and moisture conditions to make seedcoats brittle, thereby helping to break dormancy in hard-seeded species. Fire can also break dormancy and stimulate germination in hard-seeded species. The seed bank of hard-seeded species potentially can be depleted faster in CA systems compared with CT systems.

Weed seeds present on or near the soil surface are also susceptible to seed predators (Hulme 1994, Norton 2003) and environmental damage (*e.g.* Moore *et al.* 2014 with annual ryegrass). In WA, an average of 48% predation was reported for annual ryegrass, wild oats and wild radish, – higher for annual ryegrass than the other two species (Spafford Jacob *et al.* 2006). Seed size and ease of consumption were suggested as possible factors influencing predator preference. In an earlier study, predation of awned barnyard grass (*Echinochloa crus-galli*) reduced seedbank inputs from 2000 to less than 400 seeds/m^2 (Cromar *et al.* 1999). The type and amount of crop residue may affect seed predation. A Canadian study showed seed predation was higher in maize residue (31%) compared with wheat (21%) and soybean (24%) residues (Cromar *et al.* 1999). The authors suggested the type of residue was more important than total residue biomass. However, a WA study concluded that residue cover *per se* did not affect seed predation but suggested that management practices that increased the activity of seed predators (*e.g.* minimising tillage and insecticide use and retention of standing crop stubble) could be incorporated into an integrated weed management program (Spafford Jacob *et al.* 2006). When combined with other weed control tools, seed predation and seed decay in conjunction with NT may help to minimise herbicide use, risk and costs (Westerman *et al.* 2003) by reducing the seed bank and density of weed seedlings emerging in the following season.

The need for alternative weed management options

Herbicidal weed control has been fundamental to the success of Australian conservation cropping systems over the last three decades. However, a lack of effective herbicides now threatens the viability of these systems. Herbicide resistance (Boutsalis *et al.* 2012, Broster *et al.* 2013a, Owen *et al.* 2015b) and the restricted introduction of new herbicides (Duke 2012) have combined to severely restrict the availability of effective herbicide options for weed control in Australian cropping. There is an urgent need for alternative weed control technologies and approaches suitable for use in these systems (Walsh 2017).

Routine weed control options for conservation cropping systems

At present there are very few alternatives to herbicides that can be routinely used to control weeds in conservation cropping systems. The options that are available, crop competition and harvest weed seed control, are inferior to herbicides and, therefore, need to be used together and in conjunction with other weed management treatments, principally herbicides.

Enhanced crop competition through agronomic manipulation Crop competition is a pragmatic approach to manage problematic weeds, especially herbicide-resistant weeds. In the absence of control, weeds compete with crops for essential resources (Roush and Radosevich 1985). Enhancing crop competition improves resource use (water, nutrients and light) by the crop. Although crop competition occurs throughout the growing season, enhancing the competitive effects of crops are predominantly implemented at sowing. Agronomic practices such as seed size, seeding rate, row spacing, row orientation, crop cultivar (see later), and fertiliser placement can all be adjusted to ensure establishing crop seedlings have a competitive advantage over the weeds (Lemerle *et al.* 2001, Blackshaw 2004, Lemerle *et al.* 2004, Yenish and Young 2004, Zerner *et al.* 2008, Borger *et al.* 2009, Lutman *et al.* 2013, Andrew *et al.* 2015). Enhanced crop competition offers the potential for substantial weed control advantages and, importantly, yield increases. In Australia, increased crop competition through higher wheat plant densities (150 to 200 plants/m^2) has consistently resulted in substantial (>50%) reductions in growth and seed production of the dominant weed species, annual ryegrass (Lemerle *et al.* 2004), wild radish (Walsh and Minkey 2006), wild oats (Radford *et al.* 1980) and brome grass (Gill *et al.* 1987). Typically, enhanced wheat crop competition through an increase in plant densities has a positive impact on grain yield without compromising grain quality (Anderson *et al.* 2004). Similarly, the use of narrow row spacing improves crop-weed competition in favour of the crop by developing faster canopy cover and allowing less light penetration through its leaves. Likewise, changing the row orientation may help to enhance crop-weed competition and suppress problematic weeds.

Enhanced crop competition cannot be considered a standalone weed control treatment. When combined with other weed control practices, the additional impact on weed populations can be critical for weed control. For example, enhanced wheat crop competition routinely increase the efficacy of selective herbicides in controlling crop-weed populations (Kim *et al.* 2002). Importantly, this competition can lead to the control of weed populations that are resistant to the applied herbicide. For example, a 2,4-D resistant wild radish population was controlled when 2,4-D was applied at the recommended rate to resistant plants present within a competitive wheat crop (Walsh *et al.* 2009). As well as complementing herbicide activity, enhanced crop competition will likely improve the efficacy of harvest weed seed control (HWSC) strategies (Walsh *et al.* 2018a). Annual weed species infesting global wheat production systems are typically not shade tolerant (Gommers *et al.* 2013) and as indicated from competition studies, grow poorly when shaded (Zerner *et al.* 2008).

When competing with wheat for light, the likely response for shade intolerant weed species is a more upright growth habit (Morgan *et al.* 2002,Vandenbussche *et al.* 2005). This erect growth habit will undoubtedly lead to higher proportions of total seed production being located above harvester cutting height and increasing subsequent exposure to HWSC methods. Clearly then, the combined benefits of higher yield potential and enhanced weed control ensure that agronomic weed management should be standard practice throughout global wheat production systems.

Harvest weed seed control The biological attribute (weakness) of seed retention at maturity in annual ryegrass, wild radish and other annual weed species means that, at crop maturity, seed heads remain intact and at a height that enables weed seeds to be 'harvested' during grain crop harvest (Figure 4). For example, in field crops a large proportion (~60-100%) of the total seed production of the dominant annual weed species, annual ryegrass, wild radish, brome grass and wild oats can be collected during grain harvest (Blanco-Moreno *et al.* 2004, Walsh and Powles 2014, Walsh *et al.* 2018a). The efficient operation of a grain harvester expels the collected weed seed from the harvester, typically in the chaff fraction of harvest residues (Broster *et al.* 2016). Innovative Australian growers recognised the weed control opportunity of collecting the weed seeds to prevent the replenishment of weed seed banks. Subsequently, harvest weed seed control (HWSC) systems have been developed to destroy weed seeds during commercial grain crop harvest (Walsh *et al.* 2013). These include:

- chaff collection and subsequent burning;
- grazing or mulching (chaff cart);
- concentration in a narrow windrow with straw residues for subsequent burning (narrow windrow burning) (Walsh and Newman 2007);
- concentration of chaff into narrow rows (chaff lining);
- chaff collected and baled along with straw residues (Bale Direct System); and
- mechanical destruction during harvest (integrated Harrington Seed Destructor and Seed Terminator) (Walsh *et al.* 2012, 2018) (Figure 5).

Figure 4. Upright and intact annual ryegrass seed heads in mature cereal crop

HWSC is an established and effective weed control practice with Australian crop producers. It is estimated that almost one-third of Australian growers routinely use some form of HWSC to target their crop weed problems. However, although these systems have proven their efficacy on annual ryegrass and wild radish (Walsh *et al.* 2013) their efficacy on the other dominant weed species of Australian cropping, *i.e.* wild oats and brome grass, may be limited by poor seed retention at crop harvest (Walsh and Powles 2014). Given that HWSC is now a routine form of weed control, the challenge for researchers and the industry is to increase the efficacy of these systems for other weed species.

Figure 5. Current forms of harvest weed seed control (A) chaff cart, (B) narrow windrow burning, (C) bale direct system, (D) impact mill, (E) chaff lining and (F) chaff tramlining

Strategic weed control options

The strategic approach involves the use of a highly disruptive technique when weed populations reach a pre-determined critical level (*e.g.* >5.0 plant/m^2) where the aim is for maximum impact on these populations over the shortest period of time. In all weed management programs, there will be instances when weed densities increase to a level that places undue pressure on the sustainability of weed control practices as well as the production system. The greatest influence on weed control efficacy is climate and there is a wide range of seasonal conditions that can reduce the efficacy of weed control practices (*e.g.*, drought, waterlogging, frost, high temperatures). Because the threat of resistance evolution to all weed control practices increases with increasing weed densities then a major, disruptive weed control tactic is required that quickly delivers substantially lower weed numbers. When the weed population is markedly lower (*e.g.* <1 plant/10 m^2) regular crop production, including the use of routine control practices, can be resumed.

Hay, silage, manure crops and pasture phases Excessively high weed populations and the absence of effective in-crop herbicide treatments can force growers to move away from continuous cropping for one or more years enabling the use of more vigorous approaches to reduce a weed population. Techniques such as hay, silage (Gill and Holmes 1997) or manure crops (Flower *et al.* 2012) can substantially reduce annual ryegrass populations, often within one season, to quickly allow the resumption of continuous cropping. Pasture management and use of livestock provide a range of options to achieve this including spray-grazing for broadleaf weed control, spray-topping of pastures for grass weed control, pasture cleaning with paraquat or simazine (*e.g.* for *Vulpia* spp. control) in the season or two before the cropping phase, or some form of fodder conservation (hay or silage). Timing of fodder conservation can be critical to determine impact on subsequent weed population. Bowcher (2002) at Wagga Wagga in southern NSW showed that, in pastures containing *Vulpia* spp., Paterson's curse and annual ryegrass, cutting times were critical to determine weed control. An early spring cut minimised *Vulpia* spp. regrowth and seed rain whereas the other two species continued to grow and produce seed. Cutting later in the spring reduced the regrowth and seed rain of these species.

Fallow phase, cover crops and mulches Implementing a season-long fallow phase provides the opportunity to reduce weed populations significantly, typically through herbicide use, as well as to conserve soil moisture and provide a disease break (Dolling *et al.* 2006, Passioura and Angus 2010, Hunt and Kirkegaard 2011). This practice is particularly popular across the marginal rainfall areas of Australia's cropping regions where soil moisture storage is the priority during this phase (Hunt *et al.* 2013). Weeds present during the fallow phase can use significant amounts of soil moisture and so weed control throughout this period is imperative to maximise soil water storage (Hunt *et al.* 2009). Available nitrogen levels typically increase during this phase and contribute to significant yield responses in following crops (Hunt *et al.* 2013). As weeds can also benefit from the increased availability of nitrogen during the fallow phase, they must be controlled to ensure the crop yield responses. Weeds in fallow phases host crop diseases and must be removed to ensure that there is an effective 'disease break' between crops (Angus *et al.* 2015). In conservation cropping systems, tillage is not a desirable option for weed control in fallow phases: herbicides, specifically glyphosate, is relied on for weed-free fallow phases. The consequence is the widespread evolution of glyphosate resistance in several weed species (as described above) particularly in areas where fallows are a common component of cropping rotations, *e.g.* summer fallows in northern NSW and southern Qld.

Cover crops are established at the start of a fallow phase (short or long) to provide soil surface cover and replace lost biomass (Bolliger *et al.* 2006, Ruis and Blanco-Canqui 2017).Cover crop species are selected for their ability to cover the soil surface quickly as well as to produce large quantities of biomass (Fageria *et al.* 2005). Depending on the growing season and available soil moisture, cover crops are typically terminated by mowing, rolling or with herbicides well before planting a subsequent major crop (Creamer and Dabney 2009). The resulting mulch cover can suppress weed germination and emergence (Mohler and Teasdale 1993, Chauhan *et al.* 2012, Latif *et al.* 2019). In WA, black oat (*Avena strigosa* Schreb.) used as a cover crop suppressed growth of several weeds, including annual ryegrass (Flower *et al.* 2012). High biomass-producing cover crops as mulch can be a useful tool for weed suppression in CA systems (Fleet *et al.* 2018). Crops with allelopathic properties could also provide substantial weed suppression (Putnam and DeFrank 1983, Holmes *et al.* 2017). Sorghum (*Sorghum bicolor* L.), for example, releases the allelochemical sorgoleone and therefore, could be used successfully as a cover crop in CA systems (Dayan *et al.* 2010, Lee and Thierfelder 2017). Residue retention as part of CA practices could help reduce weed infestations although higher quantities than normally found in Australian dryland cropping systems are needed to substantially suppress weed germination. The use of water and N, otherwise available to the subsequent crop must be considered when contemplating the use of cover crops in semi-arid environments such as Australia.

Strategic Tillage Initially, tillage was used routinely to improve conditions for crop establishment and weed control. However, the advent and successful adoption of NT systems incorporating chemical weed control demonstrated that tillage is unnecessary for weed control (Zimdahl 2013). The greater reliance on herbicides, however, increases the prospect of herbicide-resistant weeds in these NT systems. In Australia, for example, *L. rigidum*, *Sonchus oleraceus*, *R. raphanistrum*, *Echinochloa colona*, *Conyza bonariensis*, and *Urochloa panicoides* have already evolved resistance to glyphosate (Heap 2019). However, despite the risk of evolution of herbicide resistance, these highly productive NT cropping systems need to be sustained. Strategic tillage has thus been receiving great attention among researchers and farmers in several countries, including Australia (Kirkegaard *et al*. 2014, Dang *et al.* 2015, Melander *et al.* 2015, Renton and Flower 2015, see also Chapter 7).

A strategic deep tillage used occasionally, once every 5-10 years, as a whole field or targeted at weed patches can reduce weed seedling emergence. The aim of this approach is to bury the weed seeds to a depth from which they cannot emerge (Cussans and Moss 1982) and is particularly effective against smaller weed species that cannot emerge from relatively shallow depths of burial (*i.e*. >5 cm) and have a short seedbank life. In the northern cropping region of Australia, lower densities of *C. bonariensis*, *R. raphanistrum*, *Rapistrum rugosum* and *Avena fatua* were reported in the first year following a strategic chisel tillage operation (Crawford *et al.* 2015). Similarly, another study in Queensland reported 61-90% reduced emergence of *Chloris virgata, Chloris truncata* and *C. bonariensis* after occasional tillage with harrow, gyral and offset discs compared with a NT system (McLean *et al.* 2012).

Mouldboard ploughing has also been re-considered. Here soil inversion buries the shallow weed seed banks established under long-term conservation cropping systems to a depth from which there is no emergence (*i.e*. >30 cm, Reeves and Smith 1975, Code and Donaldson 1996). Prior to the widespread adoption of conservation cropping practices, mouldboard ploughing was routinely used for weed control across the world’s cropping regions (Mas and Verdú 2003, Ozpinar 2006, Cirujeda and Taberner 2009, Lutman *et al.* 2013). Strategic mouldboard ploughing is now being used as an effective weed control practice to target weed seed banks in conservation wheat production systems. An occasional tillage of the whole field can be a useful weed control technique and when used sparingly the positive effects of NT systems on soil condition can be retained (Dang *et al.* 2015). The strategic disruptive weed control, although a major interference to crop production, reduces the selection pressure on routine chemical control practices with the aim of preserving their use for the long term. This is discussed further in Chapter 8.

Development of additional weed control opportunities

Competitive crop cultivars Cereal species and varietal differences in crop competitiveness with weeds has provided the impetus to use breeding for genetic improvement of in-crop weed control (Andrew *et al.* 2015). In wheat, comparisons across an historic 100-year set of varieties highlighted that older varieties were more competitive with weeds (Vandeleur and Gill 2004) presumably reflecting selection for improved performance in the absence of in-crop herbicides. Overseas studies have demonstrated a reduction in herbicide use of up to 50% when using weed-competitive wheats (Travios 2012, Andrew *et al*. 2015): a broader benefit is the integration of competitive varieties with cultural management (*e.g.* weed seed harvest and tillage) to reduce herbicide use and slow herbicide resistance.

Competitiveness can be considered as the partial-to-complete suppression of competing weeds to increase crop yield, or the ability of a variety to tolerate a competitor to maintain higher yields. Selection for greater tolerance of pests is a breeding strategy used for many crop insects and diseases but is of less value in weed management owing to the ongoing growth and development of the weed, and release of seed into the weed bank. Breeding of competitive crops has focused on selection of genotypes with improved access to light, water and nutrients which suppresses the growth of neighbouring weeds (Worthington *et al.* 2015). However, owing to the complex nature of plant-to-plant competition, weed suppression as a breeding strategy will likely require integration across multiple traits (Andrew *et al.* 2015). Greater early vigour, rapid leaf area development and biomass at stem elongation and altered root architecture are mechanisms used in natural plant communities (Aerts 1999). Root exudates are also used in plant defence to slow the growth of neighbouring competitors (Belz 2007).

In targeting traits of weed-competitive crop varieties, genetic modification of below-ground growth is slow and challenging owing to low heritability (*i.e*. correlation of phenotype with the underlying genotype) and difficulty in phenotyping large populations (Wasson *et al.* 2014) . The simplest approach is selection for more rapid early growth as this can be done quickly and inexpensively in large breeding populations with visual assessments of leaf size (Rebetzke and Richards 1999), LiDAR-based biomass, and Greenseeker®-based NDVI and percentage ground cover (Jimenez-Berni *et al.* 2018). Particular quantitative trait loci (QTL) have also been linked to genes associated with greater early vigour and weed competitiveness in marker-assisted selection (Coleman *et al.* 2001).

In cereals, greater leaf size and rapid early leaf area development are associated with larger seed embryos, higher specific leaf area, and use of gibberellin-sensitive dwarfing genes to reduce stem height (Rebetzke *et al.* 2004, 2014). Unfortunately, commercial wheat varieties selected for increased yield potential are ubiquitously conservative for early growth. A global survey identified 30 wide-leafed, wheat donors subsequently used in an S1 recurrent selection program to accumulate favourable genes to increase early vigour (see Chapter 17). High vigour lines derived from this program have been used to develop wheats with capacity to suppress the growth of ryegrass by up to 50% (Zerner *et al.* 2016). Ongoing breeding with these and other sometimes displaced genetic resources including landraces will be of significant value in selection away from traditional breeding objectives (*e.g.* yield potential, Rebetzke *et al.* 2018). A focus on breeding lines that are higher-yielding but also profitable and environmentally sustainable, such as occurs with weed-competitive crops, will require broader consideration of traits and alleles not present in existing breeding populations.

Impact of crop residues on weeds In stubble retention systems the role of the crop residue needs to be considered for its impact on weed establishment in subsequent crops. In the USA, Russian vetch (*Vicia villosa*) and rye (*Secale cereal*) residues were found to reduce weed density by more than 75% compared with the no-residue treatment (Mohler and Teasdale 1993). In a recent pot study in Queensland, the addition of 6 t/ha of wheat residue reduced the emergence of African turnip weed (*Sisymbrium thellungi* O.E. Schulz) by 64-75% compared with no residue (Mahajan *et al.* 2018). In similar studies, sorghum and wheat residue retention on the soil surface reduced seedling emergence of windmill grass (*Chloris truncata*) and common sowthistle, respectively (Chauhan *et al.* 2018, Manalil *et al.* 2018). Other studies have shown that the variety of the residue can determine which weeds are impacted and the effect can be influenced by seasonal conditions prior to germination (J Pratley, unpublished). The break in the season at germination time is likely to cause a bigger effect. As well as reducing weed seedling emergence, residue retention may also delay seedling emergence (Chauhan and Abugho 2013). Late emerging weed seedlings would be at a competitive disadvantage relative to the crop and thus have less impact on crop growth.

Self-weeding capability Plants have the capability to control their competition by exuding a range of chemicals into the soil environment, a process called allelopathy. Sorghum (*Sorghum bicolor*), for example, releases the allelochemical sorgoleone and therefore can be successfully used as a cover crop in CA systems (Dayan *et al.* 2010, Lee and Thierfelder 2017). Some chemicals from allelopathy have been developed as commercial herbicides (*e.g.* Callisto™ in North America and now Australia) thereby demonstrating their potency and selectivity.

While much literature exists on allelochemicals and their capability, little has been done to take advantage of them commercially (Rice 1979, Wu *et al.* 2001, Asaduzzaman *et al.* 2014). In China, allelopathic rice varieties are now commercially available (Kong *et al.* 2011) and this capability is being incorporated into rice varieties in the US (Gealy *et al.* 2014).

In most crop species, allelopathic capability has largely been bred out of commercial varieties: Bertholdsson (2004) showed for barley that capabilities of landrace lines were significantly higher in bioactivity than are modern varieties. However, some breeding lines do retain allelopathic capability but this has not been evaluated, as these lines are developed under weed free conditions and are commercially grown with the support of herbicides.

In Australia, the range of allelopathic capability of genotypes on weed species has been shown in wheat (Wu *et al.* 2001) and rice (Seal *et al.* 2004). Asaduzzaman *et al*. (2014) also showed that canola varieties had a range of allelopathic impacts (Figure 6) with consistent results in field trials over three seasons (Figure 7). It remains to be seen whether herbicide resistance will cause a rethink on the commercial possibilities of the self-weeding capabilities in crop varieties.

Mechanical weed control The opportunity for substantial cost savings, combined with the potential for introducing novel weed control technologies, is driving the demand for site-specific weed management control. However, this approach requires suitable weed detection and identification technologies that currently are not commercially available for in-crop use. The options available are based on spectral reflectance that with reasonable accuracy detect green leaf material (Scotford and Miller 2005). These systems are not suitable for in-crop use but have been successfully used for many years to control weeds in fallows. Another limitation to the adoption of site-specific weed management is that this approach only becomes economically viable once low weed densities (<1 plant/m^2) have been achieved. However, a strong focus on weed control efficacy driven by diminishing herbicide resources is helping to deliver lower than ever weed population densities in Australian dryland cropping systems. For example, in-crop wild radish populations across many areas of the WA wheat belt are well below 1 plant/10 m^2 with some farmers opting to hand weed areas in preference to applying herbicides. Thus, for these growers the demand is now for effective site-specific weed management systems.

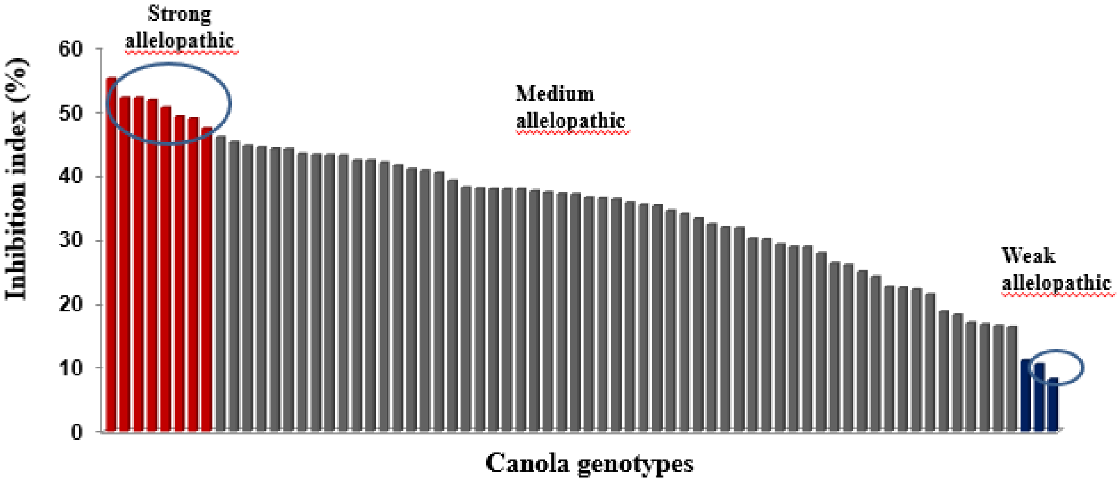

Figure 6. Inhibition index of 80 canola genotypes on root length of annual ryegrass (Asaduzzaman *et al.* 2014) with strongly allelopathic lines to the left and poorly allelopathic lines to the right

Figure 7. Impact of highly allelopathic canola genotype, Av-Opal (Left), and a poorly allelopathic genotype, Barossa (Right), on weed control (Asaduzzaman *et al.* 2014).

In low weed density situations, because of the small areas involved, and therefore the reduced impact on crop yields, detected weeds can be aggressively targeted with significant cost savings. For example, non-selective herbicides, tillage treatments, even hand weeding all become viable options. Additionally, the ability to strategically target low weed densities creates the potential for the introduction of more novel and unique weed control technologies such as electrocution (Vigneault *et al.* 1990), flaming (Bond *et al.* 2007, Hoyle *et al.* 2012), microwaves (Brodie *et al.* 2012), infrared (Ascard 1998) and lasers (Marx *et al.* 2012). There is now considerable investment in weed identification and mapping on many fronts, ranging from vehicle-mounted to UAV and even satellite systems.

The opportunity to use of range of alternate control tactics on low density weed populations within a crop is reliant on accurate detection, identification and characterisation (*i.e.* weed type, species, growth stage of the weeds. Several studies have highlighted the potential for site-specific weed control where weed detection and mapping have been separated from weed control (López-Granados 2011, Berge *et al.* 2012, de Castro *et al.* 2012).

Summary

Weed control in Australian cropping systems has undergone more dramatic changes in the last three decades than during the previous history of crop production in Australia. This period commenced with the herbicide revolution where introductions of highly effective selective and non-selective herbicides were providing excellent control of the dominant cropping weeds. These herbicides facilitated the adoption of CA and the end of tillage-based weed control systems. However, in the late 1980s there were reports of herbicide resistance, principally in annual ryegrass populations collected from intensively cropped fields. These cases heralded the start of a proliferation of herbicide resistant weed populations throughout the entire Australian cropping region during the 1990s and 2000s. The extent and severity of this phenomenon dramatically changed forever weed management and cropping practices across this region, such that from the 2000s onwards the focus has been on the conservation of diminishing herbicide resources and the development of alternative weed control technologies.

The introduction and adoption of HWSC combined with a renewed focus on crop competition have reduced somewhat the selection pressure on the few remaining herbicide resources. These combined with ‘intervention type’ weed control options for when weed populations begin to escalate have allowed growers, for the time being, to continue with conservation cropping systems. The challenge remains though for the development of highly effective alternatives to herbicides for routine use in these production systems. As we move into the next era, the expectation is that advancements in sensing, vision and computing technologies will deliver site-specific control capabilities and the potential for the use of an array of alternate approaches to weed control.

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