Herbicide resistance in wild oats (*Avena* spp.) in southern New South Wales

J.C. Broster[A], **E.A. Koetz**[B] and **H. Wu**[B]
[A] EH Graham Centre for Agricultural Innovation (Industry and Investment NSW and Charles Sturt University), Charles Sturt University, Locked Bag 588, Wagga Wagga, New South Wales 2678, Australia.
[B] EH Graham Centre for Agricultural Innovation (Industry and Investment NSW and Charles Sturt University), Wagga Wagga Agricultural Institute, PMB, Wagga Wagga, New South Wales 2650, Australia.

Summary

A random survey across the southern cereal cropping zone of New South Wales was conducted in 2007 to determine the extent of herbicide resistance in wild oat populations. In total, 113 samples were collected from the 181 properties visited. These samples were screened against the herbicide Groups (A, B, J, M and Z) commonly used for wild oat control in Australia. Resistance was present to Group A 'fop' (38%) and Group Z (10%) herbicides, increasing from 5% and 0% respectively in previous surveys (1991 and 1994). No samples were found to be resistant to clethodim, mesosulfuron, triallate or glyphosate. The significant increase in the incidence of resistance to Group A 'fop' and Z herbicides, combined with a high level of resistance in annual ryegrass from these sites, highlights the importance of adopting an integrated approach to weed management. Such an approach is also necessary for maintaining a nil or low level of resistance in Groups B, J and M, and extending the commercial life of these effective chemicals.

Introduction

In Australia, especially in New South Wales, wild oats (*Avena* spp.) is one of the most important weeds of the cropping regions. Two species, *Avena fatua* L. and *Avena ludoviciana* Durieu., form the majority of in-crop populations with a third species *Avena barbata* Pott ex Link found mainly in pastures and roadsides (Mansooji *et al.* 1992). In northern New South Wales wild oats are considered the most prevalent winter weed (Martin *et al.* 1988, Walker *et al.* 2005) while in southern New South Wales wild oats have been shown to be the second most prevalent species (Lemerle *et al.* 1996). Reasons for the importance of wild oats include seed dormancy in the soil, staggered emergence, competitiveness, and seed shedding at maturity (Jones and Medd 1997). As well as its competitive nature wild oats also host diseases which can infect cereal crops, further decreasing yield (Brown and Meagher 1970).

Because of its staggered emergence the control of wild oats has relied upon the use of herbicides, both pre-emergent and post-emergent, to control the earlier germinating seedlings that are responsible for the majority of yield loss (Jones and Medd 1997). The selective spray topping technique was developed in the 1990s to prevent seed set from the later emerging plants (Cook *et al.* 1999) but the same herbicides are used for wild oats plant kill early in the season (Medd *et al.* 1992). As the majority of wild oat seed is shed before crop harvest, non-chemical options to reduce seed rain to the soil seed bank at harvest time are not effective as control methods (Nietschke *et al.* 1996).

The ACCase-inhibiting (Group A) herbicides, aryoxyphenoxypriopionates (fops) and cyclohexandiones (dims) have been widely used for in-crop wild oat control in Australia since the release of the first of these herbicides in 1978. Until recently there have been limited alternatives to these herbicides for in-crop wild oat control placing pressure on these herbicides in the development of resistance. While herbicide resistance in wild oat populations, both in Australia and elsewhere, is well documented (Heap 2010) few surveys have been undertaken recently in Australia to determine its true extent. The last survey conducted across southern New South Wales in 1994 showed resistance only to the Group A 'fop' herbicide diclofop-methyl and only in 5% of populations (Broster *et al.* 1998). Since this previous survey ALS-inhibiting (Group B) herbicides that control wild oats have become available to Australian farmers. Wild oats populations resistant to Group A 'dim' and B herbicides (J. Broster unpublished data) and the Group Z herbicide, flamprop (Broster 2004) have been detected in southern New South Wales after 1994.

Most herbicides used for in-crop wild oat control are also used for the control of annual ryegrass (*Lolium rigidum*), and high levels of resistance have been found in annual ryegrass in New South Wales and Western Australia to Group A 'fops' and 'dims' (Broster and Pratley 2006). A recent survey of the Western Australian cropping region found 71% of wild oat populations contained plants resistant to diclofop-methyl with lower levels of resistance to many other herbicides (Owen and Powles 2009). They found wild oat plants in 43% of the surveyed paddocks compared with 72% in southern New South Wales (Lemerle *et al.* 1996).

With the higher incidence of wild oats in New South Wales compared to Western Australia and high levels of herbicide resistance in annual ryegrass across southern New South Wales (Broster *et al.* 2011), given that it has been 13 years since the last survey into wild oat resistance was conducted in southern New South Wales, it was considered important to conduct this survey to establish the extent to which herbicide resistance incidence in wild oats had changed.

Materials and methods

Sample collection

Cropping paddocks in southern New South Wales were surveyed over a four week period in November and December 2007 prior to the commencement of harvest. Paddocks were randomly selected at ten kilometre intervals, alternating left and right hand side of the survey transects where possible. The locations of all sites were recorded using a GPS unit. Seed was unable to be collected from some areas surveyed as seasonal conditions had resulted in crop and weed failure.

The paddocks were surveyed by two people walking in an inverted 'V', 150 metres into the paddock for a ten to fifteen minute period. Mature seed heads of wild oats were collected from plants along the sampling path. After collection, all the seed head samples per site were bulked. Overall, 181 paddocks were visited of which 113 contained sufficient wild oat plants to allow for resistance screening. Immediately after collection the seed samples were stored in paper envelopes in a sealed plastic container in a glasshouse (10°C minimum, 25°C maximum) until February 2008 when the species of each sample was identified, using the key from Harden (1993), and they were threshed and cleaned.

Resistance screening

In May 2009 approximately 20–30 caryopses from each of the 113 samples were planted in plastic trays (150 × 100 × 60 mm). The trays were filled with either a 50:50 peat:sand mix or a soil mix (50:50 loam:river wash sand) depending upon the herbicide to be applied. The samples were screened with five post-emergent herbicides across Groups A, B, M and Z.

Diclofop-methyl, clethodim, mesosulfuron, glyphosate and flamprop were all applied when the plants were at growth stage Z12–13 (Zadoks *et al.* 1974). Seedlings which survived the diclofop-methyl application were sprayed with sethoxydim. Plants cannot metabolize sethoxydim (Tardif and Powles 1994), therefore resistance to sethoxydim is target site resistance. One pre-emergent herbicide, triallate (Group J) was screened in this survey. For all herbicides except for mesosulfuron and triallate the seedlings were sown in the peat:sand mix, soil was used for ease of incorporating the triallate and as some Group B herbicides have soil activity all herbicides in this group are sown in the soil mix. For the triallate treatment the trays were sprayed then raked to incorporate the herbicide and the seeds were sown on top of the herbicide-treated soil and covered with 5 mm of soil.

Trays were kept in a glasshouse (10°C minimum, 25°C maximum) and were watered and fertilized as required. Two weeks after sowing all wild oats samples in all the post-emergent herbicide treatments were counted and thinned to a maximum of 10 plants per tray. Three replicates were sown for all samples except where seed numbers were limited.

All herbicides were applied at the label recommended rate and growth stage using an automated laboratory-sized cabinet sprayer with a moving boom applying a water volume of 77 L ha^{-1} equivalent from a flat fan nozzle at 300 kPa pressure. Adjuvants were added to herbicides according to label instructions (Table 1). A standard susceptible biotype and a known resistant biotype, where available, were included with each herbicide tested. Due to limited seed availability for some samples not all of the 113 samples were screened to all herbicides, or for all replicates.

Resistance evaluation

All wild oat seedlings were assessed for survival between 21 and 28 days after treatment. Seedlings in post-emergent treatments were counted before and after treatment and survival percentages were calculated. For the pre-emergent herbicide the samples were rated visually from 0 (no germination) to 10 (no visual difference from resistant control).

Samples were classified as resistant if the mean survival percentage for all replicates was greater than 20% for post-emergent herbicides or a visual score of greater than 2.5 for pre-emergent herbicides while samples with survival percentages of between 10 and 19% for post-emergent herbicides or a visual score of between 1.5 and 2.5 for pre-emergent herbicides were classed as developing resistance. Samples were classed as susceptible if survival was less than 10% or the visual score of below 1.5

Results

Of the 181 paddocks sampled, 113 (62%) contained sufficient wild oat seed to conduct the resistance testing. Resistance to diclofop-methyl was common among samples collected in this survey. Of the 113 samples screened to diclofop-methyl, 38% (43 samples) were classed as resistant or developing resistance (Table 2). Upon screening to sethoxydim, 26% of the diclofop-methyl resistant samples were also resistant or developing resistance to sethoxydim. Ten percent of samples were classed as resistant or developing resistance to flamprop. No samples were resistant or developing resistance to clethodim, mesosulfuron, triallate or glyphosate (Table 2).

Multiple resistance

Of the 113 samples, 72 were screened to all five groups of selective herbicides screened (Groups A 'fop', A 'dim', B, J and Z). The majority of the 72 samples (56%) were susceptible to all five herbicides. Forty percent (29 samples) of these samples were resistant to only one herbicide group and the remaining three samples (4%) were resistant to diclofop-methyl and flamprop. However, of the other 41 samples which were screened to fewer than five herbicides, five (12%) of these were also resistant or developing resistance to the same two herbicides. Three samples susceptible to diclofop-methyl were resistant to flamprop. However survival percentage for all three samples was below 30% (Figure 1).

After species identification 56% of samples appeared to be *A. fatua*, 28% *A. ludoviciana* and the remaining 16% contained both species. *A. ludoviciana* was the predominant species in the northern section of the survey and *A. fatua* in the south (Figure 2).

There were minimal differences between the two species in respect of resistance status. Of the *A. fatua* samples, 41%

Table 1. Herbicides and rates of herbicides used for wild oats herbicide resistance screening.

Herbicide	Group	Rate (g a.i. ha^{-1})	Adjuvant	Adjuvant rate (% v/v)
diclofop-methyl	A 'fop'	563	Chemwet1000	0.25
clethodim	A 'dim'	60	Hasten	1
sethoxydim	A 'dim'	186	DC Trate	1
mesosulfuron	B 'SU'	10	Chemwet1000	0.25
triallate	J	800	–	
flamprop	Z	225	–	
glyphosate	M	576	Chemwet1000	0.1

Table 2. Resistance levels (number or percentage) based on the survival of the wild oat populations to different herbicides applied at label rates. (R – Resistant; DR – Developing Resistance; S – Susceptible, TR = Total Resistant (Resistant and Developing Resistant combined)).

	diclofop	sethoxydim*	clethodim	mesosulfuron	triallate	flamprop	glyphosate
R	30	9	0	0	0	5	0
DR	13	2	0	0	0	6	0
S	70	32	108	83	72	94	97
Tested	113	43	108	83	72	105	97
% TR	38	26	0	0	0	10	0

* sethoxydim was only screened to the diclofop resistant populations.
R: survival >20%, except for triallate score >2.5.
DR: survival 10–20%, except for triallate score 1.5–2.5.
S: survival <10%, except for triallate score <1.5.

were resistant to diclofop-methyl and 9% to flamprop compared with 31% and 17% of *A. ludoviciana* samples while for the mixed populations resistance level was 39% and 6% respectively.

Comparison with previous surveys

Surveys in 1991 and 1994 collected samples over a smaller area than the 2007 survey (Figure 1), collecting no samples north of Cowra. These surveys did however collect some samples from further west than in 2007.

Herbicide resistance levels for Group A 'fop' has increased markedly since these surveys. The 1991 survey found 3% of samples (3/108) resistant to diclofop-methyl and in 1994 when samples were collected from 41 of the 1991 locations two samples were resistant (5%). No sample in either survey was resistant to triallate or flamprop (Broster *et al.* 1998).

Species distribution has changed markedly since the 1991 and 1994 surveys. In 1991 the majority of samples (86%) contained *A. ludoviciana*, either as the sole species (55.5%) or in combination with *A. fatua* (25.9%), *A. barbata* (2.8%) or both species (1.9%). Thirteen percent of samples contained only *A. fatua* and one sample was *A. barbata* only.

In 1995 the locations from which samples were collected in the 1994 survey were revisited and the wild oat species present identified. At this time 90% of samples contained *A. fatua* with 39% of paddocks containing only this species, 48.8% in combination with *A. ludoviciana* and 2.4% with *A. barbata*. *A. ludoviciana* was present on its own in only 7.3% of paddocks and with *A. barbata* in 2.4%.

Discussion

The level of resistance to diclofop-methyl found in this survey was lower than that found in the Western Australian survey, 38% compared with 71%. This is despite wild oats being present in a higher percentage of paddocks (62% this survey cf. 43% WA survey) in this survey.

However the reverse was true for flamprop, with 10% of samples in this survey being resistant compared with none in the Western Australian survey. As wild oats is more prevalent in New South Wales cropping paddocks and in some areas the major weed, control methods may have been specifically targeted at this weed rather than to combinations with annual ryegrass. For this reason a wild oat specific herbicide, such as flamprop, used for both in-crop weed kill and selective spray topping could have been used more often placing greater selection pressure on wild oats and enhancing evolution of herbicide resistance.

Across the surveyed area the levels of resistance in annual ryegrass were much higher, 80% for diclofop-methyl compared with 38% in wild oats, and 70% for the sulfonylurea herbicide, chlorsulfuron, compared with no wild oat populations resistant to mesosulfuron (Broster *et al.* 2011).

The lack of resistance to clethodim, mesosulfuron, triallate or glyphosate is good news. However these herbicides are under pressure, particularly in paddocks where resistance to diclofop-methyl and/or flamprop is present. Twenty one percent of ryegrass samples were resistant to clethodim (Broster *et al.* 2011), suggesting major selection pressure for resistance development to this herbicide in the accompanying wild oat populations. In Western Australia, 3% of wild oat populations were resistant to clethodim compared with 38% of annual ryegrass populations (Owen *et al.* 2007, Owen and Powles 2009).

Resistance in wild oats to Group B herbicides was not detected in this survey but has been found in samples referred to the CSU herbicide resistance testing service (J. Broster unpublished data), while, in a survey of wild oat populations in Saskatchewan, Beckie *et al.* (1999) found 18% of samples to be resistant to this herbicide group. With increased reliance on this herbicide group due to resistance to Group A 'fop' and Z herbicides, greater pressure may be placed on these herbicides with regard to resistance development.

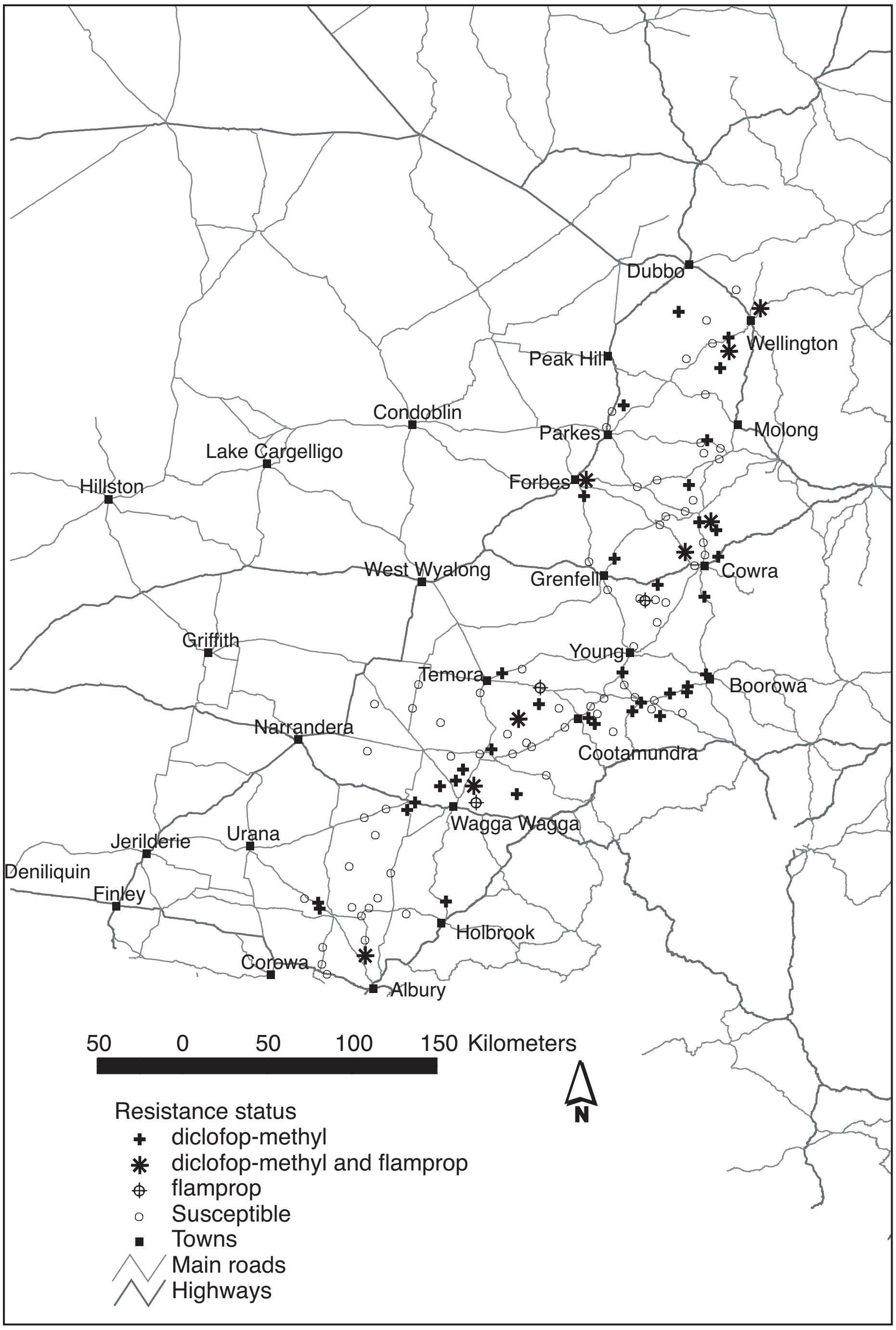

Figure 1. Sample locations showing resistance status of samples.

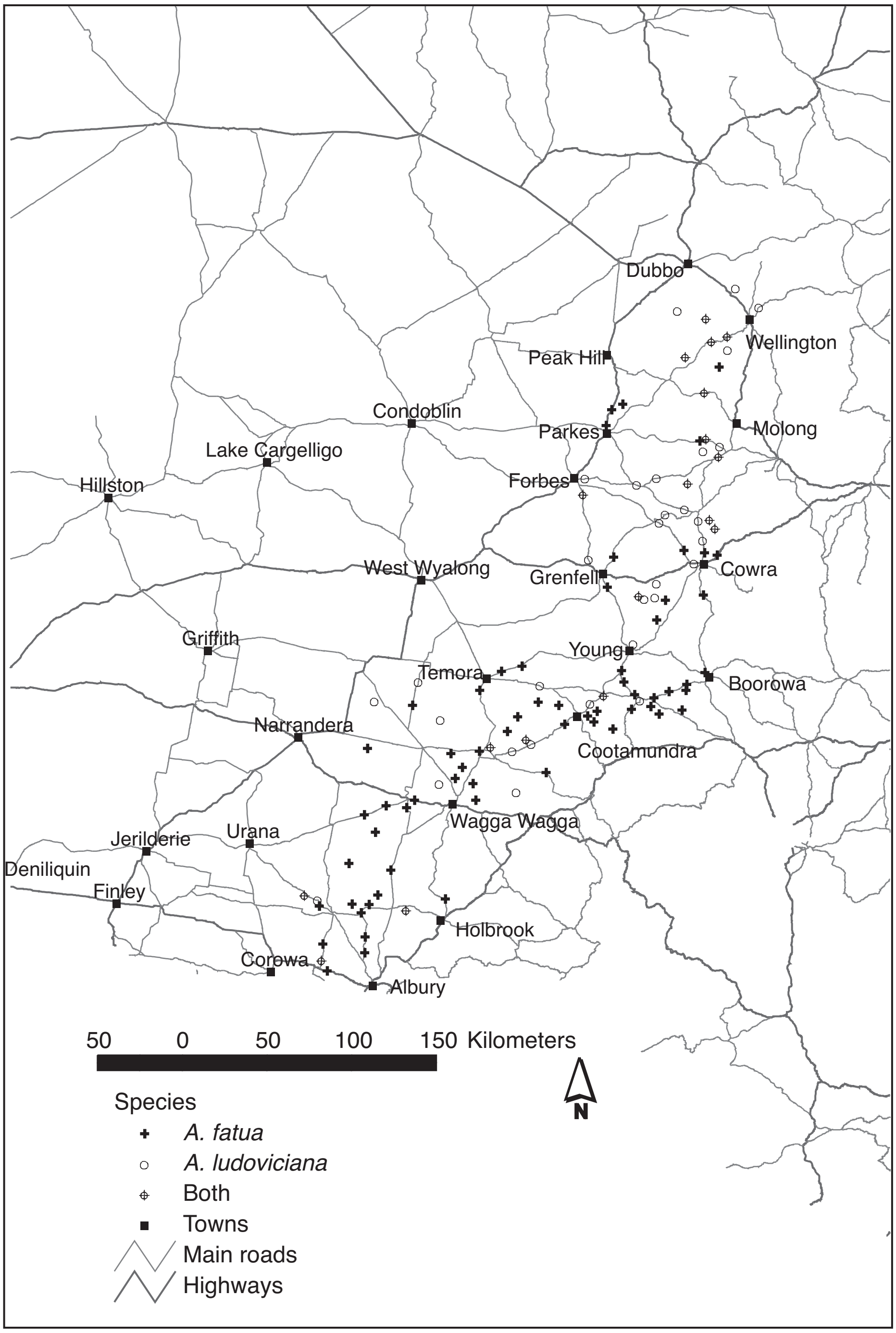

Figure 2. Sample locations showing dominant wild oat species present.

While not reported in Australia, triallate resistance has been found in several wild oat populations in Canada (O'Donovan *et al.* 1994). It required approximately 15 years of continuous use for resistance to develop. A more recent survey in Canada found 17% of wild oat populations in Saskatchewan resistant to triallate (Beckie *et al.* 2002). In Australia very few, if any, paddocks would have this history of triallate use. Data from the 1991 survey found that no paddock had received more than three applications of triallate in the previous twelve years and none of the paddocks that had received two or more applications had been cropped for more than six of the twelve years (Broster 1998).

The changes in presence of the three wild oat species and their distribution may have been influenced by the seasonal conditions between the three surveys. In Australia, Quail and Carter (1968) found that the optimum temperature for *A. ludoviciana* germination was 5°C lower than that for *A. fatua* and while both species emerge in winter, a greater percentage of *A. fatua* germinates in autumn compared to *A. ludoviciana*. In droughts, when growing seasons are shorter, seed production of mixed populations may be dominated by *A. fatua* resulting in changes in species distribution over time. In seasons with early breaks, control of the earlier germinating *A. fatua* could occur before or during sowing. This could give the later germinating *A. ludoviciana* an advantage increasing its proportion of seed set leading to mixed populations becoming *A. ludoviciana* dominant. The success of selected non-herbicidal control methods could vary depending upon the species present influencing the selection pressure for herbicide resistance.

The findings of this survey highlight some of the differences between wild oats and annual ryegrass in herbicide resistance development. Wild oats species are self-pollinating and therefore genetically less diverse than is annual ryegrass and this also influences the heritability of resistance genes. The staggered emergence of wild oats may also result in the dilution of seed supplies from resistant plants, seeds from the unsprayed plants slowing the development of resistance.

However, despite these factors herbicide resistance is still of major importance in the management of wild oats in crops. Compared with annual ryegrass, control methods, both chemical and non chemical, in wild oat populations are limited. Many of the cultural methods, such as seed collection at harvest, that have been developed for herbicide resistant annual ryegrass are not as effective on wild oats (Nietschke *et al.* 1996) placing further pressure on obtaining effective control through herbicides.

Acknowledgments

The survey was conducted as part of a larger project funded by the Grains Research and Development Corporation. The authors acknowledge the assistance of technical staff from Department of Industry and Investment NSW and students from Charles Sturt University for their assistance in the resistance screening.

References

Beckie, H.J., Thomas, A.G., Legere, A., Kelner, D.J., Acker, R.C.V. and Meers, S. (1999). Nature, occurrence, and cost of herbicide-resistant wild oat (*Avena fatua*) in small-grain production areas. *Weed Technology* 13, 612-25.

Beckie, H.J., Thomas, A.G. and Stevenson, F.C. (2002). Survey of herbicide-resistant wild oat (*Avena fatua*) in two townships in Saskatchewan. *Canadian Journal of Plant Science* 82, 463-71.

Broster, J.C. (1998). Herbicide resistance in wild oats in southern New South Wales. M. App. Sc. thesis, Charles Sturt University.

Broster, J.C. (2004). A population of wild oats (*Avena ludoviciana* Durieu) resistant to flamprop-m-methyl. Proceedings of 14th Australian Weeds Conference, eds B.M. Sindel and S.B. Johnson, pp. 432-3. (Weed Society of New South Wales, Sydney).

Broster, J.C., Koetz, E.A. and Wu, H. (2011). Herbicide resistance levels in annual ryegrass (*Lolium rigidum* Gaud.) in southern New South Wales. *Plant Protection Quarterly* 26, 22-8.

Broster, J.C. and Pratley, J.E. (2006). A decade of monitoring herbicide resistance in *Lolium rigidum* in Australia. *Australian Journal of Experimental Agriculture* 46, 1151-60.

Broster, J.C., Pratley, J.E., Slater, P.D. and Medd, R.W. (1998). Herbicide resistance in wild oats in southern New South Wales. Proceedings of 9th Australian Agronomy Conference, eds D.L. Michalk and J.E. Pratley, pp. 579-82. (Australian Society of Agronomy).

Brown, T.H. and Meagher, J. (1970). Resistance in cereals to the cyst nematode (*Heterodera avenae*) in Victoria. *Australian Journal of Experimental Agriculture* 10, 360-5.

Cook, T., Storrie, A. and Medd, R. (1999). Selective spray-topping: field testing of a new technique for reducing wild oat seed production Proceedings of 12th Australian Weeds Conference, eds A.C. Bishop, M. Boersma and C.D. Barnes, pp. 53-6. (Tasmanian Weeds Society, Devonport).

GenStat (2008). GenStat Release 11.1 Copyright 2008. Lawes Agricultural Trust.

Harden, G.J. (Ed.) (1993). Flora of New South Wales, Volume 4. (NSW University Press, Sydney).

Heap, I.M. (2010). International survey of herbicide resistant weeds, www.weedscience.org.

Jones, R. and Medd, R. (1997). Economic analysis of intergrated management of wild oats involving fallow, herbicide and crop rotational options. *Australian Journal of Experimental Agriculture* 37, 683-91.

Lemerle, D., Tang, H., Murray, G., Morris, S. and Tang, H. (1996). Survey of weeds and diseases in cereal crops in the southern wheat belt of New South Wales. *Australian Journal of Experimental Agriculture* 36, 545-54.

Mansooji, A.M., Holtum, J.A.M., Boutsalis, P., Matthews, J.M. and Powles, S.B. (1992). Resistance to aryloxyphenoxypropionate herbicides in two wild oat species (*Avena fatua* and *Avena sterilis* ssp. *ludoviciana*). *Weed Science* 40, 599-605.

Martin, R.J., McMillan, M.G. and Cook, J.B. (1988). Survey of farm management practices of the northern wheat belt of New South Wales. *Australian Journal of Experimental Agriculture* 28, 499-509.

Medd, R.W., McMillan, M.G. and Cook, A.S. (1992). Spray-topping of wild oats (*Avena* spp.) in wheat with selective herbicides. *Plant Protection Quarterly* 7, 62-5.

Nietschke, B.S., Medd, R.W., Matthews, J.M., Reeves, T.G. and Powles, S.B. (1996). Managing herbicide resistant wild oats – options and adoption. Proceedings of 11th Australian Weeds Conference, ed. R.C.H. Shepherd, pp. 546-51. (Weed Science Society of Victoria, Melbourne).

O'Donovan, J.T., Sharma, M.P., Harker, K.N., Maurice, D., Baig, M.N. and Blackshaw, R.E. (1994). Wild oat (*Avena fatua*) populations resistant to triallate are also resistant to difenzoquat. *Weed Science* 42, 195-9.

Owen, M.J. and Powles, S.B. (2009). Distribution and frequency of herbicide-resistant wild oat (*Avena* spp.) across the Western Australian grain belt. *Crop and Pasture Science* 60, 25-31.

Owen, M.J., Walsh, M.J., Llewellyn, R.S. and Powles, S.B. (2007). Widespread occurrence of multiple herbicide resistance in Western Australian annual ryegrass (*Lolium rigidum*) populations. *Australian Journal of Agricultural Research* 58, 711-18.

Quail, P.H. and Carter, O.G. (1968). Survival and seasonal germination of seeds of *Avena fatua* and *A. ludoviciana*. *Australian Journal of Agricultural Research* 19, 721-9.

Tardif, F.J. and Powles, S.B. (1994) Herbicide multiple-resistance in a *Lolium rigidum* biotype is endowed by multiple mechanisms: isolation of a subset with resistant acetyl-coA carboxylase. *Physiologia Plantarum* 91, 488-94.

Walker, S.R., Taylor, I.N., Milne, G., Osten, V.A., Hoque, Z. and Farquharson, R.J. (2005). A survey of management and economic impact of weeds in dryland cotton systems of subtropical Australia. *Australian Journal of Experimental Agriculture* 45, 79-91.

Zadoks, J.C., Chang, T.T. and Konzak, C.F. (1974). A decimal code for the growth stages of cereals. *Weed Research* 14, 415-21.