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Herbicide resistance in *Bromus* and *Hordeum* spp. in the Western Australian grain belt

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Abstract. Random surveys conducted in the Western Australian (WA) grain belt have shown that herbicide-resistant *Lolium rigidum* and *Raphanus raphanistrum* are a widespread problem across the cropping region. In 2010, a random survey was conducted to establish the levels of herbicide resistance for common weed species in crop fields, including the minor but emerging weeds *Bromus* and *Hordeum* spp. This is the first random survey in WA to establish the frequency of herbicide resistance in these species. For the annual grass weed *Bromus*, 91 populations were collected, indicating that this species was present in >20% of fields. Nearly all populations were susceptible to the commonly used herbicides tested in this study; however, a small number of populations (13%) displayed resistance to the acetolactate synthase-inhibiting sulfonylurea herbicides. Only one population displayed resistance to the acetyl-coenzyme A carboxylase-inhibiting herbicides. Forty-seven *Hordeum* populations were collected from 10% of fields, with most populations being susceptible to all herbicides tested. Of the *Hordeum* populations, 8% were resistant to the sulfonylurea herbicide sulfosulfuron, some with cross-resistance to the imidazolinone herbicides. No resistance was found to glyphosate or paraquat, although resistance to these herbicides has been documented elsewhere in Australia for *Hordeum* spp. (Victoria) and *Bromus* spp. (Victoria, South Australia and WA).

Additional keywords: emerging weeds, resistance survey, resistance evolution. Received 17

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Introduction

Grain crops (wheat, barley, maize, sorghum) are crucial to meet global food supply requirements, with weed infestations having major negative impacts on crop productivity. In Australia, broadacre cropping programs invest heavily in continuous cropping and no-till systems, which rely on herbicides for weed control (Llewellyn *et al*. 2012). Consequently, the evolution of herbicide-resistant weed populations is now widespread in Australia for the major crop weeds including *Lolium rigidum* Gaud., *Raphanus raphanistrum* L. and *Avena* spp. (Llewellyn and Powles 2001; Broster and Pratley 2006; Owen *et al*. 2007, 2014*b*; Walsh *et al*. 2007; Owen and Powles 2009; Broster *et al*. 2011; Boutsalis *et al*. 2012*a*). Globally, resistance has been documented in 238 weed species (138 dicots and 100 monocots). Weeds have evolved resistance to 22 of the 25 known herbicide modes of action and to 155 different herbicides (Heap 2014). Often, resistant populations are identified through herbicide failure in the field or large-scale surveys of agricultural regions that aim to determine herbicide resistance levels (Beckie *et al*. 2000; Burgos *et al*. 2013).

Bromus and *Hordeum* species are self-pollinated winter annual grasses and are commonly found in grain-growing regions of Australia (Lemerle *et al*. 1996; Kleemann and Gill 2006; Osten *et al*. 2007; Broster *et al*. 2010, 2012*a*, 2012*b*; Borger *et al*. 2012; Boutsalis *et al*. 2012*b*). *Bromus rigidus* Roth. and *B. diandrus* Roth have increased in importance in Australia because of increased cropping frequency, moves towards minimum tillage agriculture and limited herbicides for their control in cereal crops (Gill and Blacklow 1985; Kon and Blacklow 1988). Both of these *Bromus* species are commonly found in cropping areas in Australia receiving >250 mm annual rainfall; a third species, *B. rubens*, is generally found in the drier zones (Kon and Blacklow 1995). *Bromus diandrus* was common and widespread in the south-west of Western Australia (WA), tolerating a wide range of climatic conditions and soil types, whereas *B. rigidus* was found in a more limited range and commonly on lighter sandy soils (Kon and Blacklow 1995).

Hordeum species are problematic in grain-growing regions because they can harbour cereal diseases (Smith 1972; Cocks *et al*. 1976) and are often difficult to control in cereal crops owing to limited herbicide options (Bowran 2000). Although considered a valuable early feed source, they are undesirable to livestock at maturity, when seeds can penetrate the skin and eyes of sheep and contaminate their wool (Campbell *et al*. 1972). Cocks *et al*. (1976) found that *Hordeum* species were a common component of annual pastures and widely distributed in southern cropping regions, with *H. glaucum* growing in the drier parts of South Australia and Victoria (<425 mm), whereas *H. leporinum* was restricted to the wetter regions, although both species frequently grew together along the 425-mm rainfall margin.

A recent survey on weed incidence and species change over a 10-year period in WA found that although *L. rigidum*, *Avena* spp. and *R. raphanistrum* were the most dominant weeds of cropping fields, *Bromus* spp. and *Hordeum* spp. also ranked highly in both crop and pasture fields, occurring in up to 64% of fields depending on species, field type and year (Borger *et al*. 2012). *Bromus* and *Hordeum* species were also identified in summer fallow between February and April within the grain belt of WA, although the incidence was low, at 1–3% of fields (Michael *et al*. 2010).

Surveys elsewhere in Australia have found the incidence of these weed species to be lower than in WA. In the southern grain belt of New South Wales (NSW), Lemerle *et al*. (1996) found *Hordeum* spp. present in 26% of field sites, and *Bromus* spp. in only 9% of sites, with similar levels of infestation in that region some 15 years later (Broster *et al*. 2012*b*). In the north-eastern grain region of Australia (an area encompassing central and southern Queensland and northern NSW), *Hordeum* species were present in 1% of fields (Osten *et al*. 2007). In Tasmania, the incidence of *Hordeum* spp. and *Bromus* spp. was <10% (Broster *et al*. 2012*a*). In South Australia, *B. rigidus* was present at many sites surveyed and more commonly found in cropping fields, whereas *B. diandrus* was present in 12% of fields and more likely found near roadsides and in undisturbed areas (Kleemann and Gill 2006).

The first case of resistance to acetolactate synthase (ALS)-inhibiting herbicides in *Hordeum* spp. in WA was identified through herbicide failure in a crop field 300 km east of Perth (Yu *et al*. 2007), and subsequent cases of herbicide resistance were identified in *Hordeum* and *Bromus* species during a large-scale random survey for *Avena* spp. in 2005 (Owen *et al*. 2012*a*, 2012*b*). Worldwide, resistant populations have been reported for ALS- and acetyl-coenzyme A carboxylase (ACCase)-inhibiting herbicides in *Bromus* and *Hordeum* species (Mallory-Smith *et al*. 1999; Powles 1986; Boutsalis and Preston 2006; Escorial *et al*. 2011; Broster *et al*. 2012*a*; Owen *et al*. 2012*a*, 2012*b*). Although *Bromus* and *Hordeum* species are commonly found in grain-growing regions of Australia, little information is available in WA regarding the frequency and incidence of herbicide resistance for these weed species in cropping fields.

This is the first large-scale field survey to examine the frequency of occurrence of both *Bromus* and *Hordeum* weed species in WA crop fields, as well as a determination of their herbicide-resistance spectrum. The focus of this study was to determine the extent that these weeds are infesting WA cropping fields and the proportion of herbicide-resistant populations.

Materials and methods

Seed collection

Seed material was collected during October and November 2010 as part of a broad-scale survey evaluating herbicide resistance in key weed species (Owen *et al*. 2014*b*). Briefly, farmers were contacted and they provided farm maps, which were used to locate properties at the time of seed collection. During seed collection, 466 crop fields were chosen at random and sampled by two people walking in an inverted 'W' pattern across the field. During sampling, weed-density ratings were recorded and mature seed heads were collected from a large number of plants (50–100 plants, bulked at collection). After seed collection, seed heads were rubbed and chaff was removed by aspiration. Seed samples were stored in a warm, dry glasshouse with a daily average temperature of 26°C over the summer months (December–April) to relieve any seed dormancy (Favier 1995). In total, 91 *Bromus* and 47 *Hordeum* populations were collected for subsequent herbicide testing (Fig. 1).

Species identification

Thirty plants from each collected population were grown during 2011 and the seeds were collected at maturity to determine the species of each population. For *Bromus* spp., populations were assessed based on plant growth habit, as well as seed characteristics, as described by Kon and Blacklow (1988, 1995). Populations were designated as *B. rigidus* if the inflorescence was compact and stiff and the spikelets were heavily pigmented with reddish to black colouring. *Bromus diandrus* populations were recorded if the spikelets were long and drooping in nature. Seed appearance was also assessed randomly on selected populations by using a microscope to determine whether the hardened scar on the seed was rounded (*B. rigidus*) or acute (*B. diandrus*), to confirm visual classifications.

For *Hordeum* spp., 50 inflorescences were randomly chosen from each population at maturity and assessed under a microscope by examining the dispersal unit, consisting of a triad of single-flowered spikelets (Cocks *et al*. 1976). Species were distinguished by the size of the anthers (larger in *H. leporinum* than *H. glaucum*) in the central floret and the density of the spike (lower in *H. leporinum* than *H. glaucum*) (Cocks *et al*. 1976). Additionally, *H. glaucum* seeds were characterised by the presence of black anthers on the floret in the central spikelet (Cocks *et al*. 1976). In some cases, there appeared to be seeds from another species (unidentified) also present in the WA wheatbelt (Western Australian Herbarium 2014).

Seed germination

During May–October in 2011 and 2012 (the normal growing season for these species), seeds from each of the *Bromus* and *Hordeum* populations were placed in plastic containers containing 1% (w/v) agar–water and stored at 4°C for 12 days in the dark. After this, seeds were moved into a controlled-temperature (25°C during the day) glasshouse for 5 days before being transplanted into plastic seedling trays (300 mm by 400 mm by 100 mm) containing potting mix (50% composted pine bark, 25% peat and 25% river sand). Fifty seedlings from each population were sown for each herbicide and were kept outdoors. Known herbicide-susceptible populations from each species were used as controls for all herbicide treatments, and known resistant populations were used as positive controls for the ALS-inhibiting herbicides (Owen *et al*. 2012*a*, 2012*b*). All plants were watered and fertilised as required.

Herbicide-resistance screening

When seedlings had reached the 2-leaf stage, they were treated with a range of herbicides at Australian upper registered field rates (Table 1) together with appropriate adjuvants applied with

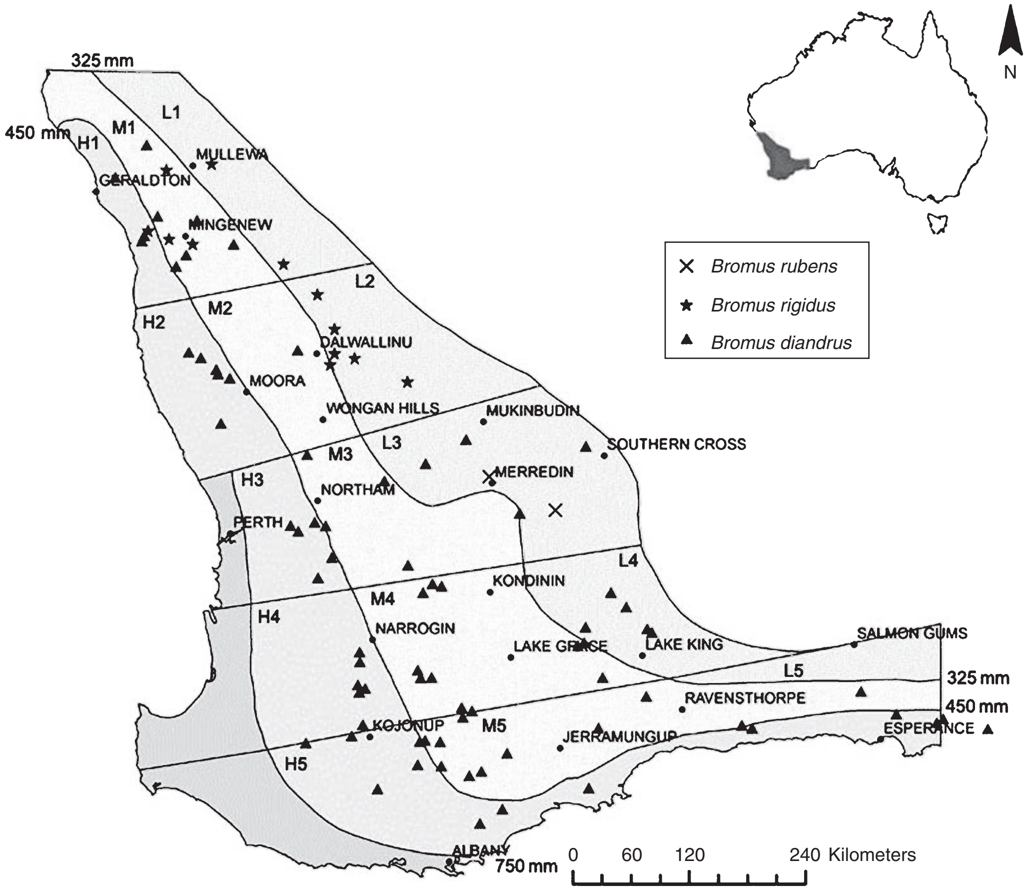

Fig. 1. Map of the south-west of Western Australia showing the agronomic zones of the grain belt and *Bromus* species distribution. Annual rainfall isohyets are shown. Rainfall regions are shown: H (high, 450–470 mm), M (medium, 325–450 mm) and L (low, <325 mm). Zones are indicated: 1 (north), 2 (north-central), 3 (central), 4 (south-central) and 5 (south).

Table 1. Herbicides and rates used for resistance screening of *Bromus* and *Hordeum* spp. populations collected in 2010 from the Western Australian grain belt

Herbicide chemical class	Herbicide mode of action	Active ingredient(s)	Field rate (g a.i. ha^{-1})
Aryloxyphenoxypropionate	ACCase inhibitor	Fluazifop	78
Cyclohexanedione	ACCase inhibitor	Clethodim	60
Sulfonylurea	ALS inhibitor	Sulfometuron	15
	ALS inhibitor	Sulfosulfuron	37.5
Imidazolinone	ALS inhibitor	Imazamox + imazapyr	23 + 10.5
Bipyridyl	Photosystem I inhibitor	Paraquat	300
Glycine	EPSPS inhibitor	Glyphosate	540

a custom-built sprayer equipped with flat fan nozzles (for spraying details see Owen *et al*. 2014*b*). The same herbicide treatments were used for both species. Herbicide treatments were repeated twice during the growing season, and results averaged for each population (always <5% variation). For *Bromus* populations treated with ALS-inhibiting herbicides, four rates of sulfosulfuron (37.5, 56.25, 75 and 112.5 g a.i. ha^{-1}) and three rates of sulfometuron (15, 30 and 45 g a.i. ha^{-1}) were used, as well as an additional treatment of 1000 g ha^{-1} of malathion 30 min before the application of 56.25 g ha^{-1} of sulfosulfuron (Owen *et al*. 2012*b*). Malathion is an organophosphate insecticide known to be an inhibitor of cytochrome P450 monooxygenases (P450s). Synergistic interactions between organophosphate insecticides and sulfonylurea herbicides are well documented (Kreuz and Fonn'e-Pfister 1992; Baerg *et al*. 1996), and studies have shown that malathion is an effective inhibitor of P450-mediated herbicide resistance in weed species such as *L. rigidum* (Christopher *et al*. 1994; Yu *et al*. 2009).

Hordeum populations were treated with three rates of sulfosulfuron (37.5, 56.25 and 75 g ha^{-1}; no malathion treatment) and a single field rate of sulfometuron (15 g ha^{-1}) (because of limited seed of most populations). Single field rates were used for all other herbicides. Assessment of plant survival was made 21 days after spraying and plants were scored as dead or alive based on whether the growing point was chlorotic and yellowing or regrowing, and by comparing the response with the known control populations. All plants that survived herbicide treatment were considered as resistant plants. Resistance was confirmed by spraying these surviving plants with double the recommended herbicide rate and testing the progeny in the following year (as below).

For *Hordeum* populations where only one or two individuals survived the ALS herbicide treatments, these plants were allowed to produce seed and the resulting progeny were tested for resistance to these herbicides.

Results

Species frequency, density and distribution

Of the 466 crop fields sampled in this survey, *Bromus* species were collected from 20% (i.e. 91 fields), although they were seen in 37% of all cropping fields surveyed. Generally, *Bromus* species were present at low numbers, with only 3% of fields having *Bromus* plant densities of >1 plants m^{-2}, 12% having densities of <1 plant m^{-2}, and 22% of fields containing *Bromus* plants that were difficult to find. The majority of *Bromus* populations were classed as *B. diandrus* (85%) and these were present in all agronomic regions of the WA grain belt (Fig. 1); two populations were classed as *B. rubens* and came from the eastern wheatbelt (zone L3); and the remainder of the populations were *B. rigidus* (13%), and were confined to the northern agricultural region (zones H1, M1, L1 and L2 see Fig. 1).

Some 26% of the 466 surveyed fields had evidence of *Hordeum* species, but in many cases either the incidence was isolated to one small patch or the plants had already shed their seed; therefore, *Hordeum* was collected from only 10% of fields. *Hordeum* densities were similar to those of *Bromus*, with 2% of fields containing >1 plant m^{-2}, 6% containing <1 plant m^{-2}, and 18% of fields containing only difficult-to-find *Hordeum* plants. The majority (79%) of populations were a mix of species including *H. glaucum* and *H. leporinum* and possible other *Hordeum* spp. which are not listed in Cocks *et al*. (1976) but are identified on the flora database for WA (Western Australian Herbarium 2014); 21% of populations contained only *H. leporinum* seeds. No population was solely *H. glaucum*. *Hordeum* species were most commonly found in the medium–low-rainfall zones of the eastern grain belt (e.g. L2, M3, L3, M4, L4, M5) although they were also present in all other cropping zones (Fig. 2).

The most common crop types were the cereals wheat (65%) and barley (13%), followed by canola (10%) (Owen *et al*. 2014*b*). *Bromus* was present in 19% of wheat crops, 24% of barley crops and 19% of canola crops, and the corresponding numbers for *Hordeum* were 13%, 7% and 4%. For other crops such as field pea and lupin, both species were present in <10% of fields, although *Bromus* was present in 40% of oat crops. However, oats accounted for only 4% of the fields surveyed.

Resistance to ACCase-inhibiting herbicides

Of the 91 *Bromus* populations screened with the ACCase-inhibiting herbicides fluazifop and clethodim, only one population, classified as *B. diandrus*, from the northern agricultural region (zone M1: Fig. 1), displayed resistance to both these ACCase-inhibiting herbicides (Table 2). This population had >85% plant survival at the Australian field application rates (Table 1), and was able to survive double the field rate, for both herbicides. All of the 47 *Hordeum* populations treated with the ACCase-inhibiting herbicides were susceptible to the herbicides tested (Table 2).

Resistance to ALS-inhibiting herbicides

A small number (13%) of *Bromus* populations, all identified as *B. rigidus* and coming from the northern agricultural region (zones H1, M1, L1 and L2) (Fig. 3), displayed resistance to the ALS-inhibiting sulfonylurea herbicides (Table 2). By contrast, no *B. diandrus* populations were resistant to the ALS-inhibiting herbicides. The resistant *B. rigidus* populations showed 100% plant survival at the Australian field rate of 37.5 g ha^{-1} of sulfosulfuron, with plant survival varying from 27% to 100% at the higher treatment rates (Table 3). These populations also had a high level of survival when treated with sulfometuron at all three rates (data not shown). When treated with malathion before the application of sulfosulfuron at 56.25 g ha^{-1}, all of the resistant populations became 100% susceptible to sulfosulfuron. All *Bromus* populations tested were susceptible to the imidazolinone herbicide mixture containing imazamox and imazapyr.

Of the *Hordeum* populations, 8% contained plants resistant to sulfosulfuron, with plant survival ranging from 5% to 20% at Australian field rates; half of these populations also had resistance to the imazamox + imazapyr mixture (Table 2). The ALS-resistant populations came from the medium–low-rainfall zones in the eastern grain belt around Northam, Kondinin and Lake Grace (zones M3 and M4, Fig. 3). The surviving progeny from these populations had 100% survival when tested at field rates of the same herbicides in the following year.

Non-selective herbicides

All *Bromus* and *Hordeum* populations were susceptible to the non-selective herbicides glyphosate and paraquat at Australian field rates (Table 2).

Discussion

Bromus and *Hordeum* grass weed species were present in 37% and 26%, respectively, of cropping fields surveyed in the WA grain belt; however, only ~20% of all fields had weed numbers that enabled a sufficiently large seed sample to be collected. This is similar to a survey by Borger *et al*. (2012), which found that the incidence of these species in cropping fields ranged from 24% to 44%. However, Borger *et al*. (2012) found that in the 10 years between surveys for cropping fields, the prevalence of *B. diandrus* had decreased by 20% (from 44% to 24%), and the genus *Bromus* was more confined to southern regions, whereas *Hordeum* incidence had increased slightly (from 32% to 37%). These changes may reflect individual years and crop management strategies, but both species rated in the top five worst weeds as ranked by farmers (Borger *et al*. 2012), indicating that these species are still problematic in cropping fields.

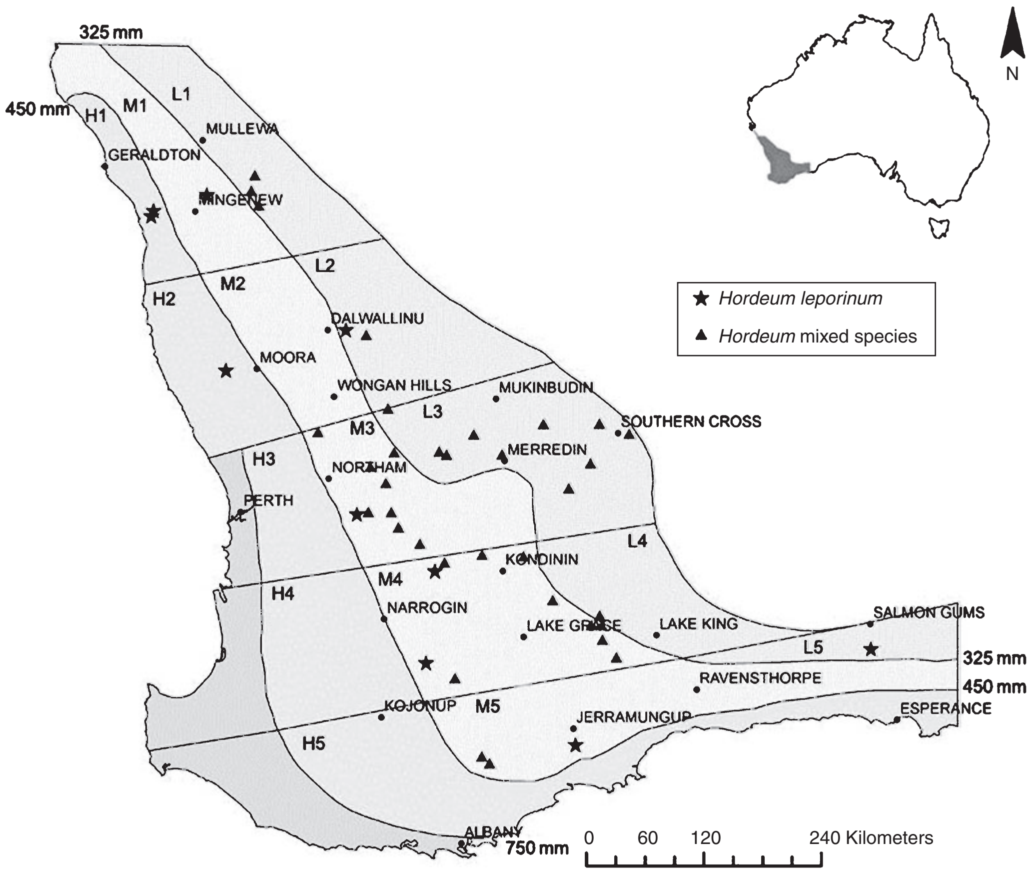

Fig. 2. Map of the south-west of Western Australia showing the agronomic zones of the grain belt and *Hordeum* species distribution. Annual rainfall isohyets are shown. Rainfall regions are shown: H (high, 450–470 mm), M (medium, 325–450 mm) and L (low, <325 mm). Zones are indicated: 1 (north), 2 (north-central), 3 (central), 4 (south-central) and 5 (south).

Table 2. Percentage of tested *Bromus* and *Hordeum* populations resistant to each herbicide group

All sulfonylurea-resistant populations were *B. rigidus*, all ACCase-resistant populations were *B. diandrus*. All ALS-resistant *Hordeum* populations were mixed species

Herbicide	*Bromus*	*Hordeum*
Sulfonylurea	13	8
Imidazolinone	0	4
ACCase	1	0
Paraquat	0	0
Glyphosate	0	0

The distribution of *Bromus* species in this survey is consistent with previous findings of Kon and Blacklow (1995), with *B. diandrus* being widespread across all zones, *B. rigidus* confined to northern agricultural regions and *B. rubens* confined to the drier areas of the eastern wheatbelt (Fig. 1). Previously reported *B. rigidus* populations resistant to ALS-inhibiting herbicides also came from the northern agricultural region of WA (Owen *et al*. 2012*b*). *Hordeum* species were less widespread than *Bromus* spp., with most *Hordeum* populations in areas with <450 mm of annual rainfall, generally within the eastern grain belt. The only populations in the higher rainfall zones were *H. leporinum*, and this is consistent with a previous study by Cocks *et al*. (1976), in which *H. leporinum* was found in areas of >425 mm of rainfall, whereas *H. glaucum* was confined to the semi-arid regions. Herbicide-resistant *Hordeum* populations have been reported previously in the eastern grain belt of WA (Yu *et al*. 2007; Owen *et al*. 2012*a*).

Changing cropping practices may affect weed flora over the following decades. A survey on weed occurrence in spring cereals in Finland over a 10-year period found that for conventional cropping systems, the abundance of weed species remained similar, although some species became more abundant with reduced tillage, and some species declined in fields with increased use of herbicides (Salonen *et al*. 2013). In Australia, the increase in herbicide usage associated with no-tillage cropping (Llewellyn *et al*. 2012) has undoubtedly increased the selection pressure for herbicide resistance. Although the major weeds (*L. rigidum*, *R. raphanistrum* and *Avena* spp.) of southern Australian cropping systems have evolved widespread herbicide resistance, herbicides are still widely used for their control and for the control of other crop weed species.

Bromus species resistant to ALS- and ACCase-inhibiting herbicides have been previously reported in Australia

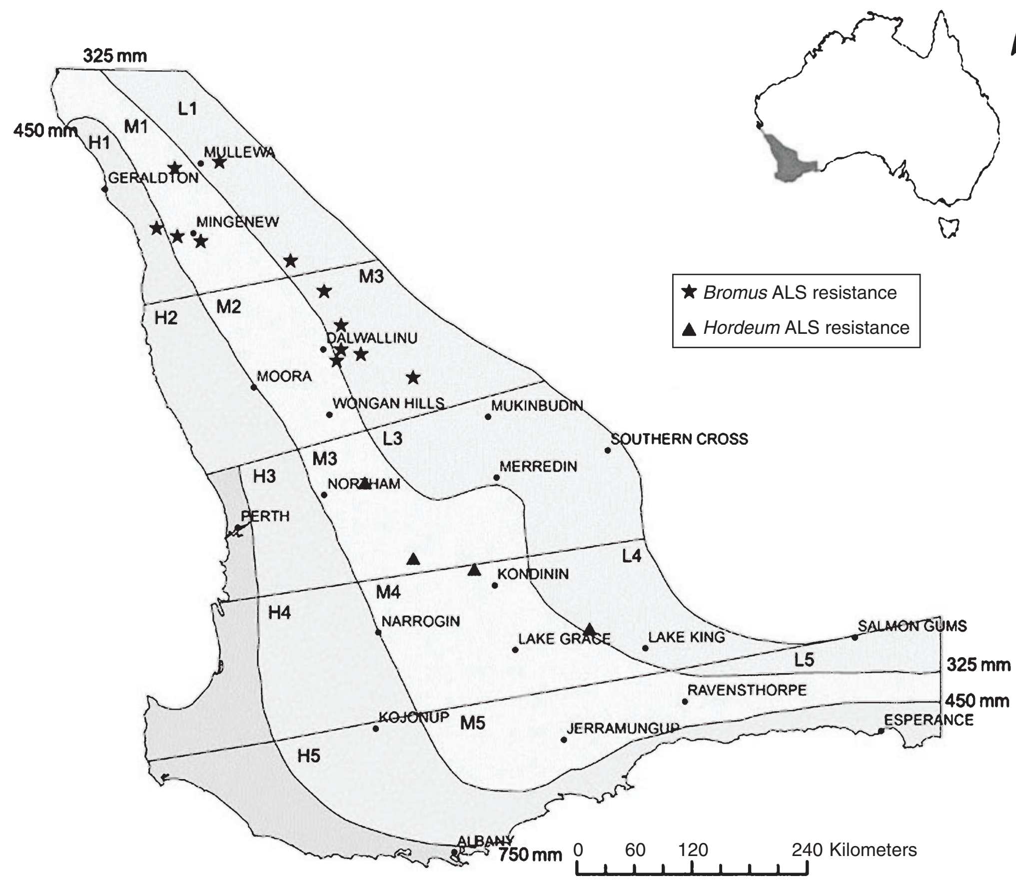

Fig. 3. Map of the south-west of Western Australia showing the location of ALS-resistant *Bromus* and *Hordeum* populations. Annual rainfall isohyets are shown. Rainfall regions are shown: H (high, 450–470 mm), M (medium, 325–450 mm) and L (low, <325 mm). Zones are indicated: 1 (north), 2 (north-central), 3 (central), 4 (south-central) and 5 (south).

Table 3. Survival (%) of *Bromus* populations treated with the ALS-inhibiting herbicide sulfosulfuron at four rates and in the presence of malathion (1000 g a.i. ha^{-1})

Values in parentheses are standard errors

Population	Sulfosulfuron rate (g a.i. ha^{-1}):				
	37.5	56.25	75	112.5	56.25 + malathion
1	100 (0)	98 (0.6)	72 (1.5)	63 (1.8)	0 (0)
2	100 (0)	96 (1.7)	96 (0.7)	72 (2.2)	0 (0)
3	100 (0)	100 (0)	80 (1.2)	90 (0.6)	0 (0)
4	100 (0)	44 (3.5)	72 (3.7)	27 (1.8)	0 (0)
5	100 (0)	66 (4.3)	58 (4.1)	82 (2.0)	0 (0)
6	100 (0)	74 (2.3)	86 (3.3)	68 (1.7)	0 (0)
7	100 (0)	95 (1.2)	88 (3.5)	50 (2.9)	0 (0)
8	100 (0)	76 (2.8)	89 (2.6)	71 (1.2)	0 (0)
9	100 (0)	39 (3.5)	30 (2.9)	50 (1.5)	0 (0)
10	100 (0)	98 (0.6)	76 (1.8)	76 (2.3)	0 (0)
11	100 (0)	46 (2.8)	36 (2.8)	46 (3.2)	0 (0)
12	100 (0)	91 (1.2)	90 (0.9)	82 (0.3)	0 (0)

(Boutsalis and Preston 2006; Broster *et al*. 2012*a*; Boutsalis *et al*. 2012*b*; Owen *et al*. 2012*b*; Heap 2014) and worldwide (Heap 2014), and recently, glyphosate resistance was detected in a population of *B. diandrus* from South Australia and in *B. rubens* from WA (Preston 2014). Commercial testing services have reported that up to 39% of *Bromus* species tested were resistant to the ACCase-inhibiting herbicides, and that 9% were resistant to the ALS-inhibiting herbicides; no resistance to other herbicide modes of action was detected (J. Broster, pers. comm.). All *Bromus* species resistant to the ALS-inhibiting herbicides collected in the present survey were found to be *B. rigidus* and came from the northern agricultural region of WA. The treatment of these resistant plants with malathion, an inhibitor of cytochrome P450 mono-oxygenases, before the application of sulfosulfuron showed that the sulfosulfuron resistance was able to be reversed. This is similar to the findings of our previous work (Owen *et al.* 2012*b*) and suggests that resistance may be due to P450 metabolism of sulfosulfuron, although this remains to be directly confirmed.

Studies assessing the seed dormancy of *Bromus* species have found that naturalised populations of *B. diandrus* generally had low levels of seed dormancy, enabling them to be controlled by agronomic practices early in the growing season (Gill and Blacklow 1985). *Bromus rigidus* had greater seed dormancy than *B. diandrus* (Gill and Carstairs 1988; Kon and Blacklow

1988) and was therefore more likely to avoid early-season weed control, be exposed to in-crop selective herbicides applied later in the season, and carry seed into the next season. This could explain why all of the *B. rigidus* populations in this study were resistant to the ALS-inhibiting herbicides, while only one population of *B. diandrus* had herbicide resistance (to the ACCase-inhibitors). This phenomenon of co-occurring seed dormancy and herbicide resistance has been recorded in *L. rigidum* populations from the WA wheatbelt (Owen *et al*. 2014*a*), and in *H. glaucum* populations in southern Australia (Fleet and Gill 2012).

Although the herbicide-resistant *Hordeum* populations collected from the field had only a relatively small number of survivors (5–20%), the progeny of these surviving individuals had 100% survival when treated with the same herbicides. Therefore, with continued selection in the field, an ever-increasing proportion of the population will survive and continue to produce resistant seed. Resistance in *Hordeum* species has been documented for the ALS-inhibiting and bipyridyl herbicides in WA (Yu *et al*. 2007; Owen *et al*. 2012*a*) and for the ACCase-inhibiting herbicides and bipyridyl herbicides in eastern Australia, including Tasmania (Powles 1986; Tucker and Powles 1991; Boutsalis and Preston 2006; Broster *et al*. 2012*a*). Currently, resistance in this genus is confined to Australia (Heap 2014).

Control of the major cropping weeds in Australia is likely to continue to be herbicide-based; thus, continued exposure of *Bromus* and *Hordeum* to these herbicides will occur. Despite the low incidence of herbicide resistance detected in this survey, continued herbicide selection in intensive crop production systems is generating resistant *Bromus* and *Hordeum* populations. Limited herbicide options are also available for the control of these species in cereal crops compared with other weed species, so the current selective herbicide options are vital to many growers. They must therefore adopt a range of strategies to control these species in their cropping systems. The use of crop production systems that employ a diverse integrated approached to weed control, and options that prevent seedset and return of seeds to the soil, are essential to reduce the impact of these currently minor weeds in the future. The use of new crop management tools such as harvest weed-seed control programs, which have been developed for *L. rigidum*, *R. raphanistrum and Avena* spp. and target seed removal at crop harvest (Walsh *et al*. 2013), could be useful in controlling additional weed species. These programs may need some modification for *Bromus* and *Hordeum* species, although testing with the Harrington Seed Destructor has shown good control for *Bromus* spp. (as reviewed in Walsh *et al*. 2013). Targeting seed removal at harvest will become a key weed-management strategy as herbicide-resistance levels increase in the minor crop weed species such as *Bromus* and *Hordeum*.

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References

Baerg RJ, Barrett M, Polge ND (1996) Insecticide and insecticide metabolite interactions with cytochrome P450 mediated activities in maize. *Pesticide Biochemistry and Physiology* **55**, 10–20. doi:10.1006/pest.1996.0030

Beckie HJ, Heap IM, Smeda RJ, Hall LM (2000) Screening for herbicide resistance in weeds. *Weed Technology* **14**, 428–445. doi:10.1614/0890-037X(2000)014[0428:SFHRIW]2.0.CO;2

Borger CPD, Michael PJ, Mandel R, Hashem A, Bowran D, Renton M (2012) Linking field and farmer surveys to determine the most important changes to weed incidence. *Weed Research* **52**, 564–574. doi:10.1111/j.1365-3180.2012.00950.x

Boutsalis P, Preston C (2006) Resistance to acetyl-coenzyme A carboxylase (ACCase)-inhibiting herbicides in *Bromus* spp. in Australia. In 'Proceedings 15th Australian Weeds Conference'. 24–28 September, Adelaide, S. Aust. (Eds C Preston, JH Watts, ND Crossman) pp. 538–540. (Weed Management Society of South Australia)

Boutsalis P, Gill GS, Preston C (2012*a*) Incidence of herbicide resistance in rigid ryegrass (*Lolium rigidum*) across southeastern Australia. *Weed Technology* **26**, 391–398. doi:10.1614/WT-D-11-00150.1

Boutsalis P, Preston C, Gill G (2012*b*) Herbicide cross resistance in *Bromus diandrus* and *B. rigidus* populations across southeastern Australia. In 'Developing solutions to evolving weed problems. Proceedings 18th Australasian Weeds Conference'. 8–11 October 2012, Melbourne, Vic. (Ed. V Eldershaw) pp. 224–228. (Weed Science Society of Victoria Inc.)

Bowran D (2000) Weed control in wheat. In 'The wheat book—principles and practice'. (Eds WK Anderson, JR Garlinge) pp. 248–253. (Agriculture Western Australia: South Perth, W. Aust.)

Broster JC, Pratley JE (2006) A decade of monitoring herbicide resistance in *Lolium rigidum* in Australia. *Australian Journal of Experimental Agriculture* **46**, 1151–1160. doi:10.1071/EA04254

Broster JC, Koetz EA, Wu H (2010) A survey of southern New South Wales to determine the level of herbicide resistance in brome grass and barley grass populations. In 'Proceedings Seventeenth Australasian Weeds Conference'. (Ed. SM Zydenbos) pp. 274–277. (Council of Australasian Weed Societies: Christchurch, New Zealand).

Broster J, Koetz E, Wu H (2011) Herbicide resistance levels in annual ryegrass (*Lolium rigidum* Gaud.) in southern New South Wales. *Plant Protection Quarterly* **26**, 22–28.

Broster J, Koetz E, Wu H (2012*a*) Herbicide resistance frequencies in ryegrass (*Lolium* spp.) and other grass species in Tasmania. *Plant Protection Quarterly* **27**, 36–42.

Broster JC, Koetz EA, Wu H (2012*b*) Weed species present in cereal crops in southern New South Wales. In 'Developing solutions to evolving weed problems. Proceedings 18th Australasian Weeds Conference'. 8–11 October 2012, Melbourne, Vic. (Ed. V Eldershaw) pp. 241–244. (Weed Science Society of Victoria Inc.)

Burgos NR, Tranel PJ, Streibig JC, Davis VM, Shaner D, Norsworthy JK, Ritz C (2013) Review: Confirmation of resistance to herbicides and evaluation of resistance levels. *Weed Science* **61**, 4–20. doi:10.1614/WS-D-12-00032.1

Campbell RJ, Robards GE, Saville DG (1972) The effect of grass seed on sheep production. In 'Proceedings Australian Society of Animal Production'. (Eds M Freer, JB Coombe, JL Davidson) pp. 225–229. (Ramsay Ware Publishing Pty Ltd: North Melbourne, Vic.)

Christopher JT, Preston C, Powles SB (1994) Malathion antagonizes metabolism-based chlorsulfuron resistance in *Lolium rigidum. Pesticide Biochemistry and Physiology* **49**, 172–182. doi:10.1006/pest.1994.1045

Cocks PS, Boyce KG, Kloot PM (1976) The *Hordeum murinum* complex in Australia. *Australian Journal of Botany* **24**, 651–662. doi:10.1071/BT9760651

Escorial C, Loureiro I, Rodríguez-García E, Chueca C (2011) Population variability in the response of ripgut brome (*Bromus diandrus*) to sulfosulfuron and glyphosate herbicides. *Weed Science* **59**, 107–112. doi:10.1614/WS-D-10-00033.1

Favier JF (1995) A model for germination rate during dormancy loss in *Hordeum vulgare*. *Annals of Botany* **76**, 631–638. doi:10.1006/anbo.1995.1141

Fleet B, Gill G (2012) Seed dormancy and seedling recruitment in smooth barley (*Hordeum murinum* ssp. *glaucum*) populations in southern Australia. *Weed Science* **60**, 394–400. doi:10.1614/WS-D-11-00203.1

Gill GS, Blacklow WM (1985) Variations in seed dormancy and rates of development of great brome, *Bromus diandrus* Roth. as adaptations to the climates of southern Australia and implications for weed control. *Australian Journal of Agricultural Research* **36**, 295–304. doi:10.1071/AR9850295

Gill GS, Carstairs SA (1988) Morphological, cytological and ecological discrimination of *Bromus rigidus* from *Bromus diandrus*. *Weed Research* **28**, 399–405. doi:10.1111/j.1365-3180.1988.tb00820.x

Heap IM (2014) International Survey of Herbicide Resistant Weeds. Online. Available at: www.weedscience.org (accessed 20 November 2014)

Kleemann SGL, Gill GS (2006) Differences in the distribution and seed germination behaviour of populations of *Bromus rigidus* and *Bromus diandrus* in South Australia: adaptations to habitat and implications for weed management. *Australian Journal of Agricultural Research* **57**, 213–219. doi:10.1071/AR05200

Kon KF, Blacklow WM (1988) Identification, distribution and population variability of great brome (*Bromus diandrus* Roth) and rigid brome (*Bromus rigidus* Roth). *Australian Journal of Agricultural Research* **39**, 1039–1050. doi:10.1071/AR9881039

Kon KF, Blacklow WM (1995) *Bromus diandrus* Roth and *B. rigidus* Roth. In 'The biology of Australian weeds. Vol. 1'. (Eds RH Groves, RCH Shepherd, RG Richardson) pp. 13–27. (RG Richardson: Melbourne, Vic.)

Kreuz K, Fonn'e-Pfister R (1992) Herbicide–insecticide interaction in maize: malathion inhibits cytochrome P450-dependent primisulfuron metabolism. *Pesticide Biochemistry and Physiology* **43**, 232–240. doi:10.1016/0048-3575(92)90036-Y

Lemerle D, Tang H, Murray GM, Morris S, Tang HY (1996) Survey of weeds and diseases in cereal crops in the southern wheat belt of New South Wales. *Australian Journal of Experimental Agriculture* **36**, 545–554. doi:10.1071/EA9960545

Llewellyn RS, Powles SB (2001) High levels of herbicide resistance in rigid ryegrass (*Lolium rigidum*) in the wheat belt of Western Australia. *Weed Technology* **15**, 242–248. doi:10.1614/0890-037X(2001)015[0242:HLOHRI]2.0.CO;2

Llewellyn RS, D'Emden FH, Kuehne G (2012) Extensive use of no-tillage in grain growing regions of Australia. *Field Crops Research* **132**, 204–212. doi:10.1016/j.fcr.2012.03.013

Mallory-Smith C, Hendrickson P, Mueller-Warrant G (1999) Cross-resistance of primisulfuron-resistant *Bromus tectorum* L. (downy brome) to sulfosulfuron. *Weed Science* **47**, 256–257.

Michael PJ, Borger CP, Macleod WJ, Payne PL (2010) Occurrence of summer fallow weeds within the grain belt region of southwestern Australia. *Weed Technology* **24**, 562–568. doi:10.1614/WT-D-09-00060.1

Osten VA, Walker SR, Storrie A, Widderick M, Moylan P, Robinson GR, Galea K (2007) Survey of weed flora and management relative to cropping practices in the north-eastern grain region of Australia. *Australian Journal of Experimental Agriculture* **47**, 57–70. doi:10.1071/EA05141

Owen MJ, Powles SB (2009) Distribution and frequency of herbicide-resistant wild oat (*Avena* spp.) across the Western Australian grain belt. *Crop & Pasture Science* **60**, 25–31.

Owen MJ, Walsh MJ, Llewellyn RS, Powles SB (2007) Widespread occurrence of multiple herbicide resistance in Western Australian annual ryegrass (*Lolium rigidum*) populations. *Australian Journal of Agricultural Research* **58**, 711–718. doi:10.1071/AR06283

Owen MJ, Goggin DE, Powles SB (2012*a*) Identification of resistance to either paraquat or ALS-inhibiting herbicides in two Western Australian *Hordeum leporinum* biotypes. *Pest Management Science* **68**, 757–763. doi:10.1002/ps.2323

Owen MJ, Goggin DE, Powles SB (2012*b*) Non-target-site-based resistance to ALS-inhibiting herbicides in six *Bromus rigidus* populations from Western Australian cropping fields. *Pest Management Science* **68**, 1077–1082. doi:10.1002/ps.3270

Owen MJ, Goggin DE, Powles SB (2014*a*) Intensive cropping systems select for greater seed dormancy and increased herbicide resistance levels in *Lolium rigidum* (annual ryegrass). *Pest Management Science* doi:10.1002/ps.3874

Owen MJ, Martinez NJ, Powles SB (2014*b*) Multiple herbicide-resistant *Lolium rigidum* (annual ryegrass) now dominates across the Western Australian grain belt. *Weed Research* **54**, 314–324. doi:10.1111/wre.12068

Powles SB (1986) Appearance of a biotype of the weed, *Hordeum glaucum* Steud., resistant to the herbicide paraquat. *Weed Research* **26**, 167–172. doi:10.1111/j.1365-3180.1986.tb00692.x

Preston C (2014) The Australian Glyphosate Sustainability Working Group. Available at: www.glyphosateresistance.org.au/ (accessed 26 September 2014)

Salonen J, Hyvönen T, Kaseva J, Jalli H (2013) Impact of changed cropping practices on weed occurrence in spring cereals in Finland—a comparison of surveys in 1997–1999 and 2007–2009. *Weed Research* **53**, 110–120. doi:10.1111/wre.12004

Smith DF (1972) *Hordeum* species in grasslands. *Herbage Abstracts* **42**, 213–223.

Tucker ES, Powles SB (1991) A biotype of hare barley (*Hordeum leporinum*) resistant to paraquat and diquat. *Weed Science* **39**, 159–162.

Walsh MJ, Owen MJ, Powles SB (2007) Frequency and distribution of herbicide resistance in *Raphanus raphanistrum* populations randomly collected across the Western Australian wheatbelt. *Weed Research* **47**, 542–550. doi:10.1111/j.1365-3180.2007.00593.x

Walsh M, Newman P, Powles S (2013) Targeting weed seeds in-crop: A new weed control paradigm for global agriculture. *Weed Technology* **27**, 431–436. doi:10.1614/WT-D-12-00181.1

Western Australian Herbarium (2014) (1998–2014) FloraBase—the Western Australian Flora. Department of Parks and Wildlife. Available at: http://florabase.dpaw.wa.gov.au (accessed 26 September 2014)

Yu Q, Nelson JK, Zheng MQ, Jackson M, Powles SB (2007) Molecular characterisation of resistance to ALS-inhibiting herbicides in *Hordeum leporinum* biotypes. *Pest Management Science* **63**, 918–927. doi:10.1002/ps.1429

Yu Q, Abdallah I, Han HP, Owen MJ, Powles S (2009) Distinct non-target site mechanisms endow resistance to glyphosate, ACCase and ALS-inhibiting herbicides in multiple herbicide-resistant *Lolium rigidum*. *Planta* **230**, 713–723. doi:10.1007/s00425-009-0981-8