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Linking field and farmer surveys to determine the most important changes to weed incidence

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Summary

An understanding of weed species incidence and patterns of change in incidence is vital in developing weed management strategies and directing future research endeavours. Weed incidence in fields in the south-west of Western Australia was surveyed in 1997 and repeated in 2008 to determine any changes. In 2008, farmers were also surveyed to determine their perception of changes to weed incidence and severity. The field survey identified a total of 194 weed species (or groups of species within a genus) in the combined survey data set (i.e. 956 sites from both field surveys). The majority of survey sites were utilised for cropping, and 152 weed species were identified within cropped fields. Between 1997 and 2008, noticeable decreases in incidence (in cropped fields) were observed for *Vulpia* spp. (−25%), *Aira caryophyllea* (−21%), *Bromus diandrus* (−20%), *Avena fatua* (−18%) and *Austrostipa* spp. (−13%), with only *Raphanus raphanistrum* (11%) and *Arctotheca calendula* (7%) significantly increasing in frequency. Farmer perception of the most severe weed problems did not always coincide with survey results of weed incidence. For example, an exceptionally common weed like *A. calendula* (with increasing incidence) was of less concern to farmers than the extremely rare *Conyza* spp. The main conclusion of this research is that the prevalence of a weed species is not always an indication of whether the species is of economic concern to industry. Therefore, it is vital to link field survey results to industry perception of weed species severity, when directing future research efforts into weed management.

Keywords: weed incidence, rare weed species, farm enterprise, *Raphanus raphanistrum*, *Hordeum* species, *Conyza* species.

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Introduction

An understanding of weed species incidence and distribution is vital to allow research to be most profitably directed in the development of weed management strategies (Webster & Coble, 1997). Weed species incidence is known to change in response to agricultural practices and environmental factors (Webster & Coble, 1997). There have been major changes to broad-scale farming systems within the 14-million-ha south-western Australian wheat belt (broad-scale winter annual grain and pasture region) in recent decades, including extensive adoption of reduced tillage practices and an increase in cereal cropping at the expense of grazed pasture and grain legume production (D'Emden *et al.*, 2008; Department of Agriculture and Food Western Australia, 2009).

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Reduced tillage and reduced grazing (methods of physical weed control) have increased reliance on chemical weed control, resulting in rapid and widespread evolution of weed populations resistant to both selective and non-selective herbicides (Walsh & Powles, 2007). Herbicide resistance does not necessarily lead to an increased abundance of weeds, but it may influence distribution or incidence of individual weed species over time (Llewellyn *et al.*, 2009). Further, reduced diversity of agricultural practices generally leads to a decline in weed species diversity (Andreasen *et al.*, 1996; Benton *et al.*, 2003). In addition to major changes in agricultural practices, climate in the south-west of Western Australia (WA) has considerably altered in the past three decades with a shift towards reduced annual rainfall (in particular warmer, drier winter growing seasons) and greater climatic variability, which may alter weed distribution or incidence (IPCC, 2007).

Changes to weed species distribution can be studied through regular surveys of the geographical distribution of weeds (Hyvonen *et al.*, 2003; Andreasen & Stryhn, 2008). While general surveys cannot establish clear connections between individual weed species and changes to the agricultural system or environment, they can identify problematic weeds within a particular region and direct future research efforts (Webster & Coble, 1997). There have been several postal and field surveys of weeds in winter cropping, summer cropping and summer fallow systems in grain-growing regions of eastern and south-western Australia (Streibig *et al.*, 1989; Felton *et al.*, 1994; Lemerle *et al.*, 1996; Jones *et al.*, 2000; Rew *et al.*, 2005; Osten *et al.*, 2007; Michael *et al.*, 2010). However, continued monitoring to investigate changes in species distribution over a period of time has not been conducted in these regions, even though it is reasonable to assume that species incidence would have altered in response to altered agricultural practices and environmental conditions.

In 1997, an extensive weed survey of the south-western Australian wheat belt was conducted during the winter growing season. This survey was repeated in 2008, revisiting the original sites, with the intention of identifying changes to weed incidence and distribution over the past decade. Further, a postal survey was distributed to farmers within the wheat belt to determine perceived changes to weed incidence over the same period. The primary hypothesis was that changes to the incidence and distribution of the most common species (i.e. those with incidence > 10%) would be evident. A secondary hypothesis was that farmer perception of the severity of individual weed species would be related to actual weed incidence and changes in weed incidence.

Materials and methods

Field survey

In 1997 and 2008, a total of 478 field sites were visited across 15 agronomic zones within the south-western Australian wheat belt (Fig. 1). Fields were monitored once between September and December prior to crop harvest, with the same sites visited in each survey. Sites

Fig. 1 Map of the south-west of Western Australia indicating the location of the 478 field sites surveyed in 1997 and 2008. Agronomic zones of the wheat belt are divided according to mean daily temperature and the length of the winter annual growing season: 1 (North), 2 (North central), 3 (Central), 4 (South central) and 5 (South), and annual average rainfall: H (High – 450–750 mm), M (Medium – 325–450 mm) and L (Low – < 325 mm).

were selected by travelling 15 km along a major road (georeferenced) and then a further 1–10 km down a minor road (exact distance randomly allocated), with non-agricultural sites excluded (i.e. native vegetation, creek line). The survey covered a total distance of approximately 7500 km. At each site, weed incidence (presence/absence data) was scored along a 30-m transect (perpendicular to the road), running from the paddock edge to within the agricultural field. Plant species that occurred along the fence lines but would not normally be found in agricultural fields (i.e. native vegetation, species that cannot grow in ruderal habitats) were excluded. Land use was classified as cropping or pasture. Crops include cereals (predominantly wheat, *Triticum aestivum* L., or barley, *Hordeum vulgare* L.), oilseed rape (*Brassica napus* L.) or legumes [predominantly lupin (*Lupinus angustifolius* L.), faba beans (*Vicia faba* L.) and chickpeas (*Cicer arietinum* L.)]. Pasture includes annual or perennial, grass- and legume-based, deliberately sown or volunteer pasture systems (Table 1). Plant species nomenclature followed that of Hussey *et al*. (1997). Several weed species were grouped at the genus level due to difficulty in identification at anthesis (i.e. *Hypochaeris* spp., *Trifolium* spp.). Species deliberately sown in pasture systems (including grass species of the *Lolium* genus and legume species of the *Trifolium*, *Medicago* or *Ornithopus* genus) were not recorded as weeds in pasture fields. Site location was classified according to agronomic zone, which is coded by mean daily temperature, the length of the winter annual growing season (from north to south, labelled 1–5) and annual average rainfall (from east to west, labelled low to very high) (Fig. 1).

To investigate changes in distribution of weed species, data were analysed using the R statistical analysis environment and its 'mgcv' package (Wood, 2010; R Development Core Team, 2011). Species with < 10% incidence were excluded from the data set, as they had too few data points to allow valid analysis. A generalised linear model (GLM) was fitted using quasibinomial as the family, to investigate the impact of year, agronomic zone, land use and their interactions on the incidence of each individual weed species. An analysis of deviance based on a chi-squared test was used to test the significance of the factors and interactions between factors. As interactions with land use were mostly significant, and to allow clearer and more meaningful comparison, the data were further divided into two subsets, cropping sites and pasture sites, and the GLM was fitted to each subset, with year, agronomic zone and their interaction as explanatory variables. This analysis allowed us to examine changes in spatial distribution patterns in a relatively coarse way, as there were significant interactions between year and agronomic zone.

Table 1 The number of sites utilised for each land use type (cropping sites including cereal, legume or oilseed rape crop sites, and pasture sites) in the 1997 and 2008 surveys. All 478 sites originally surveyed in 1997 were revisited in 2008

Land use	Number of sites 1997	2008
Crop		
Total	282	337
Cereal	212	285
Legume	56	19
Oilseed rape	14	33
Pasture	196	141
Total sites	478	478

A general additive model (GAM) was fitted (using quasibinomial as the family) to predict the probability of each species occurring based on latitude and longitude (Wood, 2010). GAM analysis can account for continuous spatial patterns in weed occurrence, as opposed to being restricted to differences between specific agronomic zones. An analysis of deviance based on a chi-squared test between a GAM fitted by year and a GAM fitted without year was used to test the significance of changes to weed occurrence patterns between the two survey years. The results of these fitted spatial predictions were mapped for each individual weed species, and species with notable spatial changes were selected for illustration in this article.

Postal survey

A paper survey was distributed to farmers within the WA wheat belt in 2008 via government and industry newsletters and websites, with 165 completed replies received. The survey asked farmers to rank their five 'worst' weeds currently and five 'worst' weeds 10 years ago. The term 'worst' was used without definition within the survey, and so those species classified as the worst weed could potentially be the most common on farm or most problematic/expensive to control. Where changes to the worst weed species had occurred, farmers were asked to state possible reasons for the change and assumed source of any new weeds. The survey also collected information on farm characteristics, including farm location, average annual rainfall, farm size and average percentage of the farm that is cropped each year.

For each weed species listed as the worst weed by any farmer, a Fisher's exact test was used to determine whether there was a significant difference in the proportion of farmers listing the species as their worst weed for 2008 versus the proportion of farmers listing the species as their worst weed for 1997. Similarly, a Fisher's exact test was used to determine whether there was a significant difference in the proportion of farmers listing a species as one of their five worst weeds for 2008 versus the proportion of farmers listing the species as one of their five worst weeds for 1997. The probability value (from the two-tailed significance test) was the cumulative probability of all outcomes that are no more probable than the observed table (GENSTAT Version 13.1, 2010). Weeds with frequencies of < 5% were excluded as there were insufficient data for valid analysis.

Results

Field survey

Survey sites were widely distributed across all major agricultural zones within the WA wheat belt (Fig. 1). In 2008, 70% of sites were utilised for cropping as opposed to pasture, compared with 59% in 1997 (Table 1). A total of 194 weed species (or groups of species within a genus), from 135 genuses and 37 families, were recorded in the combined survey data set (i.e. 956 sites from both surveys).

Within cropping sites, 152 weed species or groups of species from 36 families were recorded, the most common being the Poaceae (27%), Asteraceae (13%), Brassicaceae (9%) and Fabaceae (7%) families (Table S1). A total of 128 species were recorded at < 1% of sites in either survey. There were 13 dominant species (> 10% incidence) within cropping fields, with *Lolium rigidum* Gaudin, *Arctotheca calendula* (L.) Levyns, *Avena fatua* L. and *Raphanus raphanistrum* L. being the most common species (Fig. 2). GLM analysis indicated significant decreases in incidence between 1997 and 2008 for *Vulpia* spp. (−25%), *Aira caryophyllea* L. (−21%), *Bromus diandrus* Roth (−20%), *A. fatua* (−18%) and *Austrostipa* spp. (−13%), with only *R. raphanistrum* (11%) and *A. calendula* (7%) significantly increasing in frequency (Fig. 2, Table 2). Incidence varied significantly between agronomic zones for all species except *A. calendula* (Table 2).

General additive model analysis indicated that spatial patterns of all dominant species in cropping sites experienced a significant change between survey years ($P < 0.05$). *Raphanus raphanistrum* and *A. fatua* were prevalent throughout the central and northern wheat belt in 1997; however, in 2008, *A. fatua* had a more restricted distribution, whereas *R. raphanistrum* increased its distribution spreading southwards. *Bromus diandrus* and *Vulpia* spp. were present throughout the wheat belt in 1997, but were mainly restricted to the south in 2008 (Fig. 3). *Trifolium* spp. and *Crassula* spp. were common to the south in 1997, but had increased incidence in the central and northern wheat belt in 2008 (data not presented).

Within pasture sites, 139 weed species or groups from 29 families were recorded, the most common being the Poaceae (32%), Asteraceae (19%), Brassicaceae (7%) and Caryophyllaceae (4%) families (Table S1). A total of 112 species were recorded at < 1% of sites in either survey. There were 15 dominant species (> 10% incidence) in pasture sites with *A. calendula*, *Hordeum* spp., *Vulpia* spp. and *B. diandrus* the most common species in 1997 and *A. calendula*, *Hordeum* spp., *Hypochaeris* spp. and *B. diandrus* the most common species in 2008 (Fig. 2). GLM analysis indicated significant decreases in occurrence between 1997 and 2008 for *Vulpia* spp. (−26%), *A. caryophyllea* (−21%), *B. diandrus* (−21%), *Bromus hordeaceus* L. (−8%), *Romulea rosea* M.P.de Vos. (−7%) and *Austrostipa* spp. (−7%), while increases were observed for *R. raphanistrum* (22%), *Hypochaeris* spp. (19%), *Crassula* spp. (12%), *Erodium cicutarium* (L.) L'Her. (11%) and *A. calendula* (10%) (Fig. 2, Table 2). Incidence varied significantly between agronomic zones for all species except *A. calendula*.

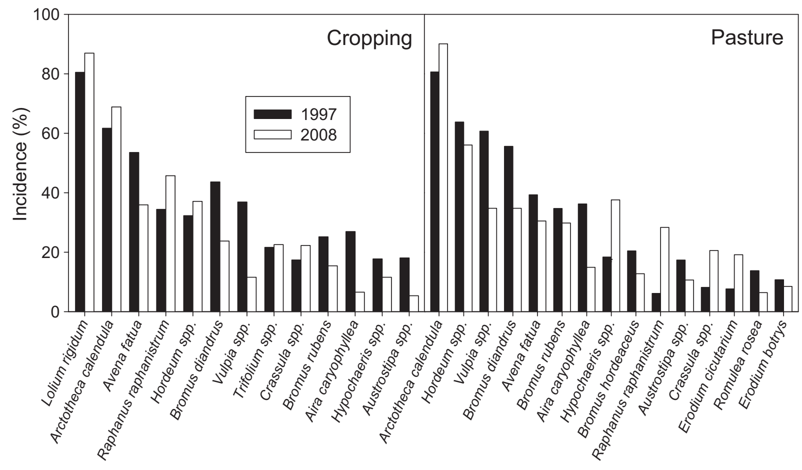

Fig. 2 Weed species present within a minimum of 10% of cropping or pasture fields between the 1997 and 2008 surveys.

Table 2 Influence of year and agzone (agronomic zone, indicated in Fig. 1) on the incidence of dominant weeds species (> 10% incidence, averaged over both survey years) within cropping or pasture fields

Land use	Weed species	Year	Agzone	Year × Agzone	Incidence (%)
Cropping	*Lolium rigidum* Gaudin		***	*	84
	Arctotheca calendula L.	*			65
	Avena fatua L.	***	***		46
	Raphanus raphanistrum L.	***	***	**	40
	Hordeum spp.		***		38
	Bromus diandrus Roth	***	***		31
	Vulpia spp.	***	***		23
	Trifolium spp.		***	*	21
	Crassula spp.		***	***	21
	Bromus rubens L.		***		20
	Aira caryophyllea L.	***	**	**	16
	Hypochaeris spp.		**		14
	Austrostipa spp.	***	**	*	11
Pasture	*Arctotheca calendula* L.	*			85
	Hordeum spp.		*		61
	Vulpia spp.	***	***		50
	Bromus diandrus Roth	***	***	*	47
	Avena fatua L.		***		36
	Bromus rubens L.		***	*	32
	Aira caryophyllea L.	***	**		27
	Hypochaeris spp.	***	***	**	26
	Bromus hordeaceus L.	*	***		17
	Raphanus raphanistrum L.	***	***		15
	Austrostipa spp.	*	**	**	14
	Crassula spp.	***	***		13
	Erodium cicutarium (L.) L'Her.	***	***		12
	Romulea rosea M.P.de Vos.	**	***		11
	Erodium botrys (Cav.) Bertol.		***	**	10

$P < 0.001$***, $P < 0.01$**, $P < 0.05$*, blank n.s.

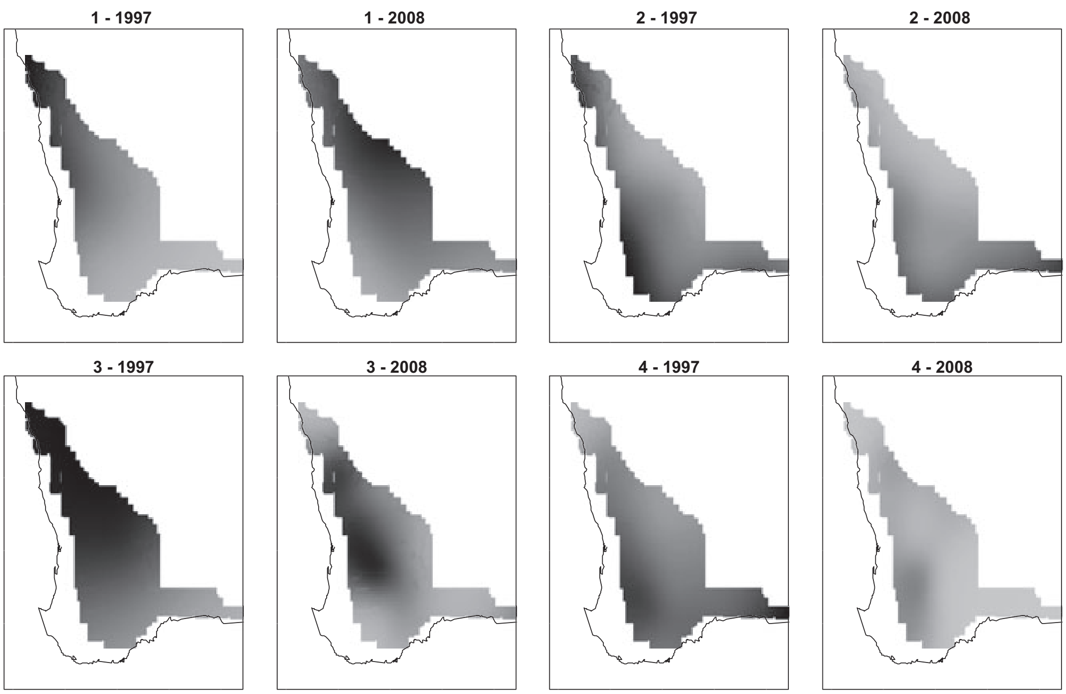

Fig. 3 Distribution maps of *Raphanus raphanistrum* (1), *Bromus diandrus* (2), *Avena fatua* (3) and *Vulpia* spp. (4) in the cropped sites in 1997 and 2008, resulting from the generalised additive model analysis (GAM). On each map, grey indicates no incidence and black indicates high incidence of the weed species.

As for cropping sites, GAM analysis indicated that spatial incidence of all dominant species in pasture sites experienced a significant change between survey years ($P < 0.05$). *Raphanus raphanistrum* had an increase in incidence throughout the northern and central wheat belt in 2008. *Vulpia* spp. and *B. diandrus* were found throughout the wheat belt in 1997, but *Vulpia* spp. were less common in the central and northern wheat belt, and *B. diandrus* was less common in the northern wheat belt in 2008 (Fig. 4). Further, *A. calendula*, *Hypochaeris* spp., *Hordeum* spp., *A. fatua*, *Bromus rubens*, *A. caryophyllea*, *B. hordeaceus*, *Austrostipa* spp., *R. rosea*, *E. botrys*, *Crassula* spp. and *E. cicutarium* were all found throughout the wheat belt in 1997. In 2008, *A. calendula*, *Hypochaeris* spp., *Crassula* spp. and *E. cicutarium* had increased incidence, but the remaining species had reduced incidence (data not presented).

Postal survey

The 165 survey respondents were widely distributed throughout the wheat belt, with average annual rainfall for each farm ranging from 200 to 600 mm. The average farm size (arable land) was 3600 ± 207 ha, with 67 ± 2% of the farm utilised for cropping rather than pasture.

A total of 18 weed species were listed as the worst weed in either 1997 or 2008 by more than 5% of respondents (20 weed species listed in total). In both years, *L. rigidum* was most commonly listed as the worst weed, but fewer farmers nominated *L. rigidum* as the worst weed in 2008 (53% of farmers) compared with 1997 (69%, Table 3). Likewise, fewer farmers nominated *A. fatua* as the worst weed in 2008 (2%) compared with 1997 (9%). There was a substantial increase in farmers listing *R. raphanistrum* as their worst weed in 2008 (20%), followed to a lesser extent by *Conyza* spp. (6%) and *Hordeum* spp. (4%). A total of 18 species were listed within the five worst weed species by more than 5% of respondents in 1997 or 2008 (56 species listed in total). *Lolium rigidum* and *R. raphanistrum* were the first and second most commonly listed weeds for both 1997 and 2008. The majority of individual species within the five worst weeds did not generally differ over the past decade, except for a decrease in *A. calendula* and *Rapistrum rugosum* (L.) All. and an increase in *Conyza* spp. (Table 3).

Half of all the farmers (53%) stated that their worst weed on farm had changed in the past decade, suggesting that the weed had been introduced from a neighbouring farm (15%), another paddock within the farm (13%), in contaminated grain or hay (1%) or due to movement of livestock or machinery (6%). Fifty-two per cent of these respondents indicated that the new worst weed in 2008 was always present on the farm, but not considered to be a major problem in the past. The worst weed species was most commonly listed as a problem in cereals (wheat, barley, oats) (37%), across all enterprise

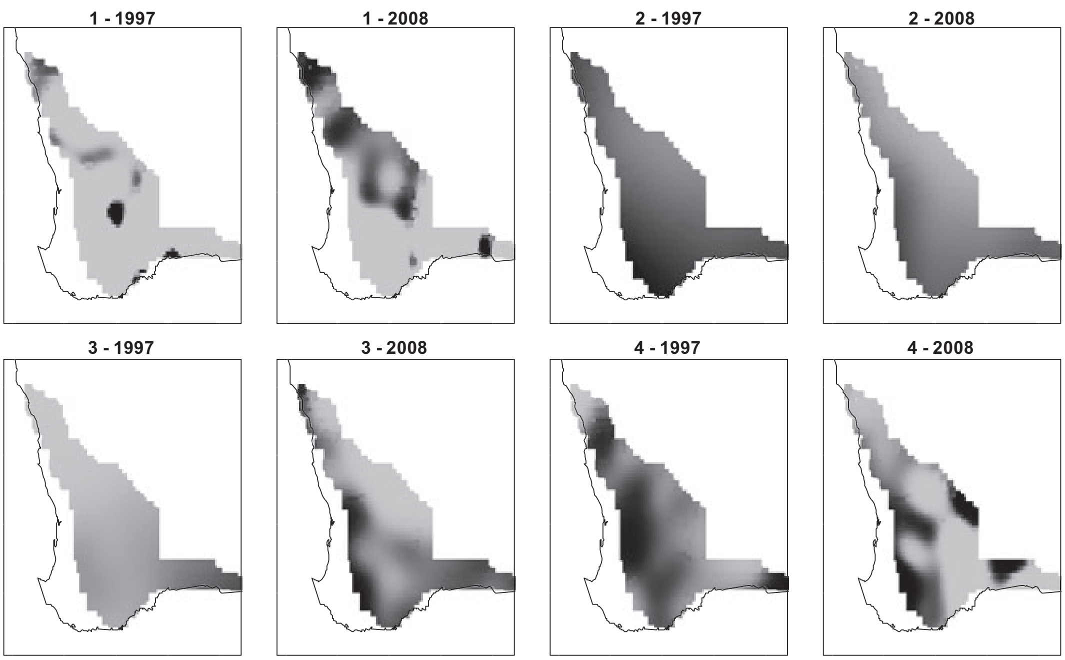

Fig. 4 Distribution maps of *Raphanus raphanistrum* (1), *Bromus diandrus* (2), *Hypochaeris* spp. (3) and *Vulpia* spp. (4) in the pasture sites in 1997 and 2008, resulting from the generalised additive model analysis (GAM). On each map, grey indicates no incidence and black indicates high incidence of the weed species.

Table 3 Weed species ranked by farmers as either the worst weed or within the top five worst weeds on their farm in 1997 and 2008 together with changes in ranking between the two surveys

Farmer ranking	Species	Percentage of farmers		Change %	P value
		1997	2008		
Worst weed	*Lolium rigidum* Gaud	69.1	52.5	−16.7	**
	Raphanus raphanistrum L.	12.4	32.4	20.0	**
	Conyza spp.	0.0	6.3	6.3	**
	Hordeum spp.	0.6	5.0	4.3	*
	Malva parviflora L.	0.8	4.2	3.3	
	Bromus spp.	4.5	3.2	−1.3	
	Emex australis Steinh.	3.4	2.7	−0.7	
	Mesembryanthemum spp.	0.7	2.2	1.5	
	Avena fatua L.	9.4	1.9	−7.5	*
Top five worst weeds	*Lolium rigidum* Gaud	94.5	90.3	−4.2	
	Raphanus raphanistrum L.	76.4	84.8	8.5	
	Bromus spp.	32.1	43.6	11.5	
	Hordeum spp.	35.2	35.2	0.0	
	Citrullus lanatus (Thunb.) Matsum. & Nakai	29.7	32.7	3.0	
	Avena fatua L.	38.8	31.5	−7.3	
	Cucumis myriocarpus Naudin	22.4	24.2	1.8	
	Arctotheca calendula L.	40.0	19.4	−20.6	**
	Emex australis Steinh.	27.3	17.6	−9.7	
	Vulpia spp.	15.8	15.2	−0.6	
	Malva parviflora L.	5.5	11.5	6.1	
	Conyza spp.	1.2	10.3	9.1	**
	Polygonum aviculare L.	9.1	7.3	−1.8	
	Tribulus terrestris L.	2.4	6.7	4.2	
	Chloris spp.	2.4	6.7	4.2	
	Mesembryanthemum spp.	1.8	5.5	3.6	
	Rapistrum rugosum (L.) All.	12.1	3.6	−8.5	**
	Erodium spp.	5.5	1.2	−4.2	

$P < 0.001$***, $P < 0.01$**, $P < 0.05$*, blank n.s.

types (23%) or across all crops (15%), followed by pastures (8%), legumes (7%), fallows (chemical winter fallow or summer fallow, 3%) or oilseed rape (2%). The perceived cause of changes to the worst weed was herbicide resistance (39%), reduced tillage (30%), increased cropping and changes to the cropping rotation (13%), unknown (11%), climate change (5%) and soil issues (2%). Several farmers who indicated that climate had caused the change in weed species had noted increased summer rainfall over the summer/autumn fallow, or had noted unusually dry conditions during the winter/spring growing season. Note that not all respondents answered questions on changes to the worst weed and some gave more than one answer, so resulting percentages do not sum to 100%.

Discussion

This study has shown that there have been significant changes to the distribution and incidence of major weed flora in the WA wheat belt since the initial field survey in 1997. However, the farmer's perception of the most severe weed species did not always correspond to actual weed incidence. For example, *L. rigidum* was the most common weed species of cropping fields for both survey years, with no significant change in incidence. However, there was a significant reduction in the number of farmers nominating it as the worst weed. This species has become more difficult to control, as there has been a substantial increase in levels of herbicide resistance in *L. rigidum* populations (Owen *et al.*, 2007; Walsh & Powles, 2007). While *L. rigidum* is a beneficial pasture species, the area sown to pasture has reduced, and so the potential grazing benefits from this species have declined (Department of Agriculture and Food Western Australia, 2009). It is possible that the concerted effort into improved control of this weed through the adoption of integrated weed management strategies has ensured that farmers now consider this weed easier to manage, in spite of fewer herbicide options and reduced benefits from grazing (McGillion & Storrie, 2006).

Conversely, there was a significant increase in the number of farmers who perceived *R. raphanistrum* to be their worst weed, which correlated with an increased incidence of this species in both cropping and pasture fields. The spread of *R. raphanistrum* and the increased perception of this species as the worst weed problem are probably due to increased herbicide resistance (Walsh *et al*., 2007). The resistance issue is most severe in the northern wheat belt, and results from the increased prevalence of continuous cropping (reduced pasture production), as this weed is highly competitive with crops and can be controlled by grazing in pastures (Eslami *et al*., 2006; Walsh *et al*., 2007). The increasing farmer concern highlights the need for research into improved control of *R. raphanistrum*, particularly non-chemical control methods that can be utilised in the northern wheat belt (Walsh & Newman, 2007; Walsh *et al*., 2007, 2012).

There was also an increased perception of *Hordeum* spp. and *Conyza* spp. as major weed species. Overall incidence of *Hordeum* spp. did not change between survey years, but herbicide resistance is becoming an increasingly severe issue for this weed species (McGillion & Storrie, 2006). There is also evidence that germination patterns (dormancy levels) of *Hordeum* spp. have altered as the agricultural system favours selection of those ecotypes with staggered emergence, rather than ecotypes with high emergence rates at the start of the year (Gill & Fleet, 2012). Further, many herbicides used against this weed offer suppression rather than control (Moore & Moore, 2010). The decade of 2000–2010 had dryer growing seasons in WA than the 1990s, and so crop competition against suppressed weeds may have been less effective in this decade (due to less vigorous crops) than when the herbicides were originally introduced (IPCC, 2007; Moore & Moore, 2010). However, new pre-seeding selective herbicides that can suppress this weed prior to crop establishment (as opposed to suppression in-crop) may provide better control as the young (and more vulnerable) crop is protected to a greater degree (Moore & Moore, 2010).

Conyza spp. generally emerge in spring crops in Mediterranean-type climatic systems and so should have been evident at the time of the field survey (Wu, 2009). Yet, incidence of *Conyza* was too low to allow analysis (*Conyza* spp. found in 0–1.2% of cropping fields in 1997 to 2008 and 0.5–0.7% of pasture fields, Table S1). The increased perception of farmers that *Conyza* spp. is their worst weed or within their top five worst weeds is probably a reflection of the difficulty and expense involved in controlling this species. *Conyza* spp. have staggered emergence in spring crops, seedlings are hard to target due to crop cover, and farmers are generally more concerned with harvest preparation than weed control at this time of year (Wu, 2009). The plants are tolerant of herbicides when they are past the seedling stage and generally require very high rates of herbicide or sequential herbicide application to achieve a commercially acceptable level of control (Wu, 2009; Moore & Moore, 2010). Given the success of this genus in the eastern states of Australia and internationally, it is likely that *Conyza* spp. will become a major problem in WA farming systems (Powles, 2008; Wu, 2009). Farmer perception indicates that this weed is the most prominent new threat to the WA wheat belt, and further research is required to determine how rapidly this weed will spread to farms and how best to control the species.

Common species such as *A. fatua*, *Vulpia* spp. and *Bromus* spp. had reduced distribution, and this was generally reflected in the farmers' perceptions. These species do not have widespread resistance to herbicides, and there are a range of management options available to control them (McGillion & Storrie, 2006; Owen & Powles, 2009). However, it is not possible to tell whether the reduced distribution is due to these weeds being managed more successfully or whether environmental changes, such as the generally drier climate, affected weed growth (McGillion & Storrie, 2006; IPCC, 2007). These weeds are among the most common in the WA wheat belt, but herbicide resistance will be slow to develop as they are self-pollinated with reduced genetic variability compared with grasses like *L. rigidum* (Kon & Blacklow, 1990; Loo, 2005; Owen & Powles, 2009).

Several other weed species were common but not regarded as highly problematic by farmers, including *A. calendula*, *Crassula* spp., *Trifolium* spp., *A. caryophyllea*, *Austrostipa* spp. and *Hypochaeris* spp. *Arctotheca calendula* was listed as one of the top five worst weeds in 1997 by 40% of farmers, but only by 19% in 2008. The other species were not regarded as one of the worst or top five worst species. *Arctotheca calendula*, *Crassula* spp., *Trifolium* spp. and *A. caryophyllea* are relatively short (or prostrate), poorly competitive species (Hussey *et al*., 1997). Further, they are generally controlled by pre-seeding and in-crop control tactics directed towards removal of more problematic weeds like *L. rigidum* and *R. raphanistrum* (Hussey *et al*., 1997; McGillion & Storrie, 2006). *Austrostipa* spp. and *Hypochaeris* spp. are more common in undisturbed areas (pastures and roadsides) than within cropping fields (Hussey *et al*., 1997; Lamp *et al*., 2001). *Trifolium* spp. are deliberately established legume pasture species, and increased incidence likely reflects the success of recent breeding programmes to improve the persistence of this species in the WA cropping system (Nichols *et al*., 2007). Likewise, *A. calendula* and *Austrostipa* spp. have some value as stock feed in dryer areas (Lamp *et al*., 2001; McGillion & Storrie, 2006).

It is clear that farmers perceived their major weeds as a larger issue in crops rather than pastures. This is likely to be mainly due to the greater proportion of crop compared with pasture fields and the larger profits obtained from crop rather than pasture enterprises

(Department of Agriculture and Food Western Australia, 2009). Further, none of the weeds identified here are highly poisonous to stock. While some weeds may outcompete more desirable pasture species, many provide valuable forage (Lamp *et al*., 2001; McGillion & Storrie, 2006). Farmers were aware that the increased intensity of cropping, the minimum tillage system and the reduced rotational diversity were likely to be exacerbating their weed problem (Walsh & Powles, 2007; D'Emden *et al*., 2008; Department of Agriculture and Food Western Australia, 2009). While it is unlikely that this awareness will directly drive major changes to the farming system, it is a favourable outcome that farmers understand the reasons why weed incidence changes, as their understanding will improve implementation of control strategies developed to address altered weed incidence due to the altered agricultural system.

In the current studies (1997 and 2008), transects were started at the roadside, because surveying was carried out in spring, when in-crop weed control would have removed several species. Generally, agronomic weed species in WA will also grow on the roadside where it is illegal to control them, as desirable native species on the roadside would also be eradicated. Therefore, surveying the roadside indicated those species that were likely to have been present in fields but removed by weed control practices. Obviously, there are some species that do not grow on the roadside and so were not captured in the survey where they had been effectively controlled in fields. Conversely, there are some species that grow on roadsides and in cropping fields, but are more common in undisturbed roadsides, like *Austrostipa* spp. and *Hypochaeris* spp. (Hussey *et al*., 1997). These species may be over-represented in the results of agricultural weed incidence, due to the inclusion of roadside weeds. These problems could have been avoided by surveying fields (and not the roadside) at the beginning of the growing season, when weed control practices were less likely to have removed species. However, it is very difficult to accurately identify weed species at the seedling stage (Hussey *et al*., 1997). Also, many weed species emerge during winter/spring rather than autumn, so these species could not be captured by surveys conducted in autumn at the beginning of the growing season. The survey time of spring/early summer was selected as the time when it was most practical to view (and correctly identify) the largest number of weed species in this Mediterranean agricultural system.

A conclusion of this work is that combined data from the field survey and farmer perception of weed issues indicate that future research funding should aim to develop improved management strategies for *R. raphanistrum*, *Hordeum* spp. and *Conyza* spp. These three species/groups of species are not all among the most common weeds, but they are an increasingly severe issue for farmers. Another conclusion is that the very common weed species may not all need future research work to improve management. Some of the most common species had reduced incidence, indicating that current management strategies are adequate. Even where incidence of common species had increased (i.e. *A. calendula*) or remained constant, there is little point developing management strategies if farmers do not consider the weed to be of major concern (and so are unlikely to apply expensive management strategies). A more important outcome of this work is that it highlights the importance of combining survey results with industry perception of weeds. The results of weed surveys are used to determine the direction of future research efforts (and funding) (Webster & Coble, 1997). However, as the current study concludes, weeds that are highly prevalent and increasing in distribution like *A. calendula* may not be of concern to farmers. Conversely, incidence of weeds like *Conyza* spp. may be so rare that they are dismissed from a survey due to insufficient data for accurate analysis and yet pose a major threat to industry. An understanding of the incidence of weed species must be combined with (i) a consideration of the management strategies already available for the species and (ii) industry perception of each weed species, if future research efforts are to be profitably directed by survey work.

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Supporting information

Additional supporting information may be found in the online version of this article.

Table S1 Incidence of weed species in cropping or pasture fields as recorded in two surveys conducted in 1997 and 2008.

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