Interactions between crop sequences, weed populations and herbicide use in Western Australian broadacre farms: findings of a six-year survey

Authors: Harries, Martin, Flower, Ken C., Scanlan, Craig A., Rose, Michael T., and Renton, Michael

Source: Crop and Pasture Science, 71(5) : 491-505

Published By: CSIRO Publishing

URL: https://doi.org/10.1071/CP19509

CSIRO PUBLISHING
Crop & Pasture Science, 2020, **71**, 491–505
https://doi.org/10.1071/CP19509

Interactions between crop sequences, weed populations and herbicide use in Western Australian broadacre farms: findings of a six-year survey

Martin Harries[A,B,F], *Ken C. Flower*[B], *Craig A. Scanlan*[C], *Michael T. Rose*[D], *and Michael Renton*[E,B]

[A]Department of Primary Industries and Regional Development (DPIRD), Government of Western Australia, 20 Gregory Street, Geraldton, WA 6530, Australia.
[B]UWA School of Agriculture and Environment and UWA Institute of Agriculture, The University of Western Australia, Perth, Stirling Highway, WA 6009, Australia.
[C]Department of Primary Industries and Regional Development (DPIRD), Government of Western Australia, 75 York Road, Northam, WA 6401, Australia.
[D]NSW Department of Primary Industries, Bruxner Highway, Wollongbar, NSW 2477, Australia.
[E]School of Biological Sciences, The University of Western Australia, Perth, Stirling Highway, WA 6009, Australia.
[F]Corresponding author. Email martin.harries@dpird.wa.gov.au

Abstract. Six years of survey data taken from 184 paddocks spanning 14 million ha of land used for crop and pasture production in south-west Western Australia were used to assess weed populations, herbicide resistance, integrated weed management (IWM) actions and herbicide use patterns in a dryland agricultural system. Key findings were that weed density within crops was low, with 72% of cropping paddocks containing fewer than 10 grass weeds/m^2 at anthesis. Weed density and herbicide resistance were not correlated, despite the most abundant grass weed species (annual ryegrass, *Lolium rigidum* Gaudin) testing positive for resistance to at least one herbicide chemistry in 92% of monitored paddocks. A wide range of herbicides were used (369 unique combinations) suggesting that the diversity of herbicide modes of action may be beneficial for reducing further development of herbicide resistance. However, there was a heavy reliance on glyphosate, the most commonly applied active ingredient. Of concern, in respect to the evolution of glyphosate resistant weeds, was that 45% of glyphosate applications to canola were applied as a single active ingredient and area sown to canola in Western Australia expanded from 0.4 to 1.4 million hectares from 2005 to 2015. In order to minimise the weed seed bank within crops, pastures were used infrequently in some regions and in 50% of cases pastures were actively managed to reduce weed seed set, by applying a non-selective herbicide in spring. The use of non-selective herbicides in this manner also kills pasture plants, consequently self-regenerating pastures were sparse and contained few legumes where cropping intensity was high. Overall, the study indicated that land use selection and utilisation of associated weed management actions were being used successfully to control weeds within the survey area. However, to successfully manage herbicide resistant weeds land use has become less diverse, with pastures utilised less and crops with efficacious weed control options utilised more. Further consideration needs to be given to the impacts of these changes in land use on other production factors, such as soil nutrient status and plant pathogens to assess sustainability of these weed management practices in a wider context.

Additional keywords: break crops, herbicide resistance, integrated weed management, rotation.

Received 9 December 2019, accepted 1 April 2020, published online 12 May 2020

Introduction

Weed control is a major cost in grain cropping systems worldwide. In Australian annual cropping systems weeds are estimated to reduce revenue by AUD $745 million per annum (Llewellyn *et al*. 2016). Land use selection, commonly referred to as rotation or crop and pasture sequence, is a fundamental tool used to manipulate weed populations within dryland agricultural ecosystems.

Substantial changes in land use across southern Australia over the recent decades have resulted in a greater frequency of cropping at the expense of pasture and livestock production and a switch from legume to oilseed crops (Kirkegaard *et al*. 2011; ABS 2016). This has occurred in most agroecological zones of south-west Western Australia (WA), across an area of 14 million ha, with sheep numbers declining from 26 million to 14 million from 2005 to 2015 (Harries *et al*. 2015; Planfarm and Bankwest 2016).

Weed control practices have also changed within WA farming systems in recent decades. Extensive adoption of no-tillage and minimum-tillage practices (Llewellyn *et al*. 2012; Llewellyn and Ouzman 2019), has provided many benefits such as reduced soil erosion, improved soil structure and greater water use efficiency (Derpsch *et al*. 2010; Fisher and Hobbs 2019). However, this practice alters weed seed dynamics (Chauhan *et al*. 2006) and eliminates cultivation as a method of weed control, resulting in a greater reliance on herbicides. Indeed the total area on which herbicides are applied in WA are estimated to have increased from 3.9 to 9.5 million ha over the period from 1980 to 1989 (Gill 1995), additionally since 1989 cropped area rose from 5.0 million to 8.0 million ha (ABS 2016). Novel integrated weed management strategies utilised within reduced tillage systems have also been developed and adopted, such as application of herbicides in spring to sterilise weed seeds before maturity and shedding and various methods of capturing weed seeds during harvest (Walsh and Powles 2007; Norsworthy *et al*. 2012).

Under these cropping systems several economically important weed species have evolved resistances to commonly utilised herbicides including acetolactate synthase (ALS) inhibitors, microtubule inhibitors, acetyl-CoA carboxylase (ACCase) inhibitors, carotenoid biosynthesis inhibitors, photosystem II inhibitors, synthetic auxins and 5-enolpyruvylshikimate-3-phosphate synthase (EPSP) inhibitors (Heap 2020). In particular herbicide resistant populations of annual ryegrass (*Lolium rigidum*) and wild radish (*Raphanus raphanistrum*) are now widespread throughout the cropping zone of WA (Walsh *et al*. 2007; Owen *et al*. 2014) and are estimated to have a 10-fold or greater economic impact than any other weed species with revenue loss due to each species estimated at AUD $50.3 and $40.1 million per annum respectively (Llewellyn *et al*. 2016). Further evolution of resistances to herbicides presents a major risk to the sustainability of the no-till cropping system, due to the dependence upon the remaining effective herbicides for weed control (Gianessi 2013).

Diverse rotations have been shown to reduce the likelihood of severe weed problems in minimum tillage cropping (Nichols *et al*. 2015), by enabling the use of a wide range of herbicide active ingredients (Derksen *et al*. 2002) and IWM strategies – both of which are advantageous to slow or prevent the evolution of herbicide resistant weed populations (Busi *et al*. 2013; Powles and Gaines 2016). Diverse rotations can also provide other benefits including improved plant nutrition, breaks in disease cycles and opportunities to spread market risk (Bullock 1992; Kirkegaard *et al*. 2008; Davis *et al*. 2012; Seymour *et al*. 2012).

Recent changes in land use, widespread adoption of no-tillage and evolution of herbicide resistant weeds in south-west WA raises concerns about the long-term sustainability of current cropping systems and a reassessment of the interactions between land use and weed populations is timely. The research objective was to identify relationships between land use and weed populations within south-west WA. This was done through documenting changes over time in crops and weeds as well as farmer practices in a series of selected paddocks, encompassing several distinct agroecological zones. The findings would also be relevant to dryland farming systems elsewhere in the world.

Materials and methods

Data sources

Data was obtained from the Focus Paddocks database (Harries *et al*. 2015). This comprised 184 paddocks monitored over 6 years across south-west WA (Fig. 1). Field measurements were from a geo-referenced 1 ha area within each paddock. Farmers were interviewed annually. Wheat (*Triticum aestivum*) was grown in all paddocks in the first year of monitoring, followed by farmer-specified land uses in the following years. Climate data were interpolated for each paddock co-ordinate using the SILO (Scientific Information for Land Owners) database (Jeffrey *et al*. 2001).

Weeds

The one hectare area was divided into quarters of 25 ×100 m and weeds were sampled in a zig zag transect through each. Weed species and density were recorded from five quadrats per transect (20 quadrats), each quadrat 0.1 m^2 (0.33 ×0.33 m). Alternatively, if weeds were in noticeable patches, numbers were rated in five areas of 0.5 m by 10 m per transect and converted to plants/m^2 using an exponential scale, as described by Rew *et al*. (2000). Measurements were taken twice per year, at 2–4 weeks after emergence and at anthesis. If pastures were present, detailed species composition was assessed once per year, in spring.

Herbicide use

Data on herbicide use were from 614 paddock-years (368 wheat, 91 canola (*Brassica napus*), 44 barley (*Hordeum vulgare*), 38 lupin (*Lupinus angustifolius*), 56 pasture and 17 other crop or fallow). Data shown in supplementary material (see Supplementary Material table S1 available at the journal's website). Analysis of herbicide use patterns was conducted by categorising the data according to land use, sowing date and date and rate of herbicide applications. For pastures that were not sown (i.e. regenerated/volunteer pasture), the first rains of autumn ($\geq$15 mm within a 1day period after 1 April) were taken as the sowing date. The mass of herbicide active ingredient (a.i.) applied was calculated. Combinations of active ingredients were identified based on the products in each tank mix.

Herbicide resistance

Seed from annual ryegrass was collected from 125 paddocks at physiological maturity and tested for resistance to herbicides at Charles Sturt University, Wagga Wagga Australia, as per Broster *et al*. (2019) and Broster and Pratley (2006). Six herbicides with different modes of action were tested individually, not as mixtures. Application rates in the resistance tests were at half label/recommended rate (0.5 × R), full recommended rate (1.0 × R), and twice recommended rate (2.0 × R). The recommended rates of the six herbicides tested were: diclofop-methyl (Hoegrass) at 375 g/ha, (Weed Science Society of America Group 1, Herbicide Resistance

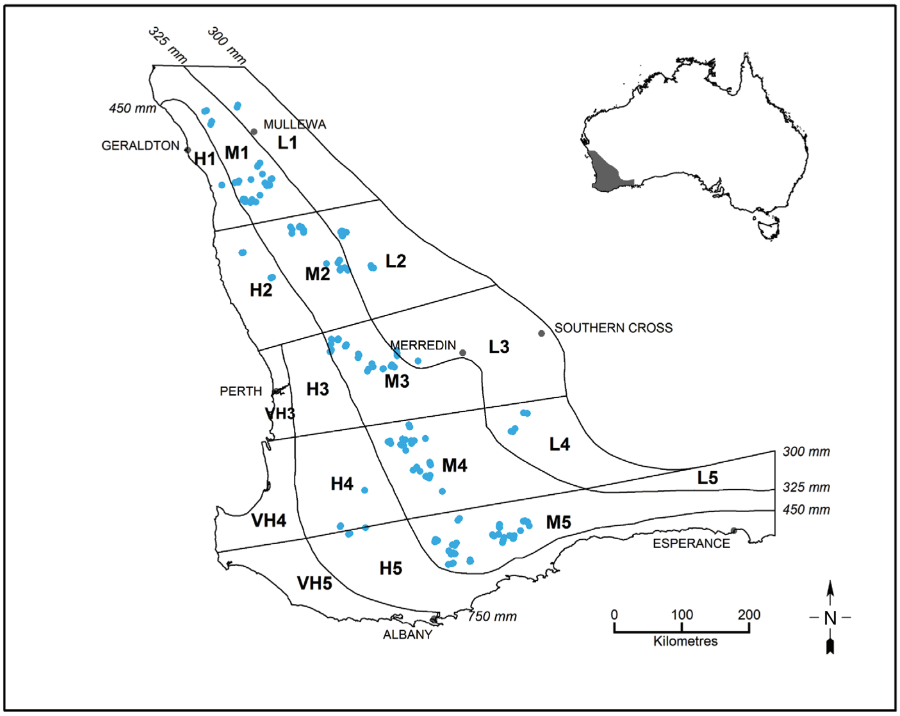

Fig. 1. Location of 184 survey paddocks (blue dots) from 2010 to 2015 in the south-west of WA. Boundaries depict Western Australian Department of Primary Industries and Regional Development (DPIRD), agroecological zones according to rainfall. Letters refer to rainfall zones: VH, very high; H, high; M, medium; L, low. Numbers refer to regions northern (1 and 2), central (3 and 4) and southern (5) agricultural regions.

Action Committee Group A); clethodim (Select) at 120 g/ha (1, A); triasulfuron (Logran) at 26 g/ha (2, B); atrazine (Atrazine) at 1800 g/ha (5, C); trifluralin (Treflan) at 800 g/ha (3, D) and glyphosate (Roundup) at 576 g/ha (9, M).

For post emergent herbicides, the methodology of the testing laboratory was to categorise populations as resistant if $\geq$20% of seedlings survived application at 1.0 $\times$ R. For pre-emergent herbicides ratings of establishment were, 0 (no germination) to 10 (similar to susceptible annual ryegrass control). Populations were considered resistant if rated $\geq$2.5. In addition, we defined a more quantitative and general measure of resistance by calculating the mean plant survival percentage (MS%) over all herbicides at all rates.

Integrated weed management

Records of 528 paddock-years were utilised to determine an integrated weed management index (IWMI). Likely control of the existing annual ryegrass seed bank or seed production (future seed bank) was assigned using default parameter values of the ryegrass integrated management (RIM) computer simulation model (Lacoste 2014). Categories and % control included: whole paddock burn (50% control), hay cutting (90%), grazing (80%), pre-sowing tillage (15%), knife-point sowing tillage (20%), knockdown (pre-sow non-selective herbicide application, 35%), double-knockdown (two applications of pre-sow non-selective herbicide at least a week apart, 75%), crop competition (plant density by crop species, low 10%, medium 20%, high 40%), seed set control 1 (crop-top, herbicide application near crop maturity to sterilise immature weed seed, 70%) seed set control 2 (pasture-top, herbicide application to pastures in spring to stop seed set, 90%), seed set control 3 (swathing 40%) and seed capture (chaff cart or windrow 85%). Crop competition was assigned as low, medium or high according to recommended densities for wheat and barley as <100, 110–150 and >150 plants/m^2; canola as <25, 25–40 and >40 plants/m^2; and lupin as <30, 30–45 and >45 plants/m^2 respectively (Anderson and Garlinge 2000; Harries *et al*. 2008; French *et al*. 2016).

Statistical analysis

All analyses were conducted using R statistics software ver. 3.6.0. Descriptive statistics include standard error represented as $\pm$. ANOVA was used to test differences in means between multiple groups. If significantly different, ($P < 0.05$) further analysis was conducted to differentiate between groups using unpaired *t*-tests and the pairwise function within the R statistics software or Tuckey HSD tests. A Chi-square test for homogeneity was conducted to assess whether herbicide usage was in proportion to the frequency at which each land use was employed. This analysis used the proportion of paddock-years of each land use within the herbicide dataset. The frequency distribution of the total amount of herbicide a.i. applied/paddock-year was assessed using Shapiro-Wilk tests and Q-Q plots. Diversity of herbicide combinations applied was assessed using Shannon diversity index. Julian dates were used for analysis of herbicide application timing and sowing dates. The effect of IWMI on grass weed density/m^2 in the following autumn was assessed by segregating weed density into three levels; (low <3; medium 3–75; high <75), and IWMI into two levels; (above or below 100), and applying a Chi-square test.

Regression tree analysis (RT) was conducted, using the r.part package of the R statistics software (ANOVA method) (Therneau and Atkinson 2019), to identify which variables had greatest influence on grass weed populations in the following autumn. Variates included, annual rainfall, land use, region, number of herbicides applied, MS% and IWMI. Since the first regression tree split strongly on annual rainfall and pasture land use, a second regression tree analysis was conducted without annual rainfall as a variate and without any pasture data to look for more subtle relationships.

Results

Land use

A total of 1017 paddock-years of land use data were accumulated. This incorporated an additional 330 paddock-years to that reported in Harries *et al*. (2015), however the segregation of land uses and regional distribution remained similar: wheat 60%, canola 12%, barley 6%, lupin 6%, pasture 12% and other land uses 4%, which comprised of chickpea (*Cicer arietinum*), faba bean (*Vicia faba*), fallow, field pea (*Pisum sativum*), oat (*Avena sativa*), oaten hay and vetch (*Vicia* spp.). Regionally more wheat and lupin were grown in the northern agricultural region (NAR), more pasture and barley in the southern agricultural region (SAR) and canola accounted for around 14% of paddock-years in each region. Data are shown in Supplementary table S2.

Climatic conditions of the study area

Western Australia has a Mediterranean-type climate in which the major growing season runs from May to November. There were large differences in rainfall between years with annual averages of 246 mm in 2010 (±4.1), 480 mm in 2011 (±5.3), 304 mm in 2012 (±3.9), 366 mm in 2013 (±5.5), 353 mm in 2014 (±5.2) and 335 mm in 2015 (±4.1). Mean annual rainfall during the survey period in the NAR was 326 mm (±3.9), central agricultural region (CAR) 334 mm (±4.7) and SAR 394 mm (±6.6).

Weeds

Species diversity

Weed species recorded across all land uses included annual ryegrass (64% of paddock-years), barley grass (*Hordeum glaucum* and *H. leporinum*, 12%), brome grass (*Bromus* spp., 8%), blue lupin (*Lupinus cosentinii*, 2%), Cape weed (*Arctotheca calendula*, 27%), doublegee (*Emex australis*, 5%), silver grass (*Vulpia myuros* and *V. bromoides*, 2%), wild radish (18%) and 38 economically unimportant minor weed species and volunteer crop or pasture plants (<6%).

Pasture species composition was categorised as legume pasture, annual ryegrass, broadleaf weed and grass weed. Across all paddock-years total plants/m^2 within pastures was 1098 (±174), 1471 (±143) and 1474 (±75) for the NAR, CAR and SAR respectively. Legume pasture plants accounted for 7, 49 and 40% of species in the NAR, CAR and SAR respectively, annual ryegrass plants 6, 14 and 35%, broadleaf weeds 67, 31 and 14% and grass weeds 20, 6 and 11% (Fig. 2). For each species category the number of plants/m^2 differed between regions: legume pasture, annual ryegrass, broadleaf weed, ($P < 0.001$) and grass weed ($P = 0.018$). Pairwise comparisons of *t*-tests between regions indicated pasture paddocks in the NAR had fewer ryegrass plants/m^2 than the CAR ($P = 0.033$) and the SAR ($P < 0.001$), fewer legume pasture plants/m^2 than other regions ($P < 0.001$), more grass weeds/m^2 than the CAR ($P = 0.006$) but not the SAR ($P = 0.208$), and more broadleaf weeds/m^2 than the CAR ($P = 0.009$) and SAR ($P < 0.001$). Hence there was a strong regional influence with pasture density and composition poorest in the NAR.

Frequency

Weeds were observed in 84% of paddock-years in the survey; grass weeds in 86% of pastures and 68% of crops and broadleaf weeds in 94% of pastures and 50% of crops. By region, the frequency of grass weeds was 71% (NAR), 58% (CAR) and 86% (SAR) and the frequency of broadleaf weeds was 47, 54 and 66% respectively. Canola paddocks had the highest proportion without either grass or broadleaf weeds at anthesis. As expected pastures frequently contained a high density of species considered to be weeds within crops, although around 15% of pastures were sparse, containing few plants/m^2 (Fig. 3).

Density

Overall mean density was 115 (±13) plants/m^2, but the distribution of densities was highly skewed towards zero, with a median density of 6 plants/m^2. With pastures excluded, total

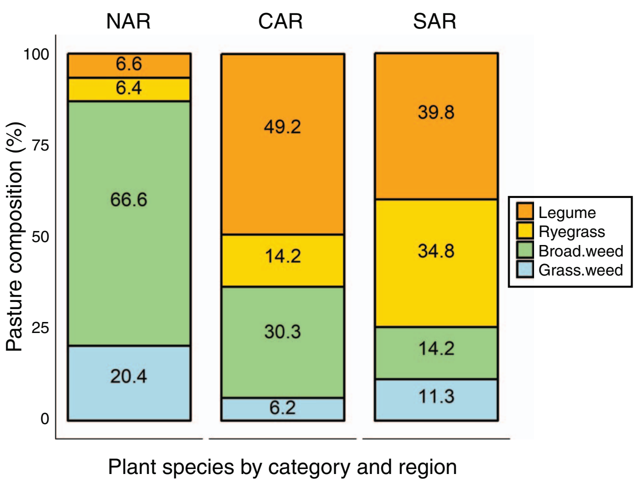

Fig. 2. Pasture composition, represented as % of plants within the four categories (legume plants, annual ryegrass plants, broadleaved weeds and grass weeds), across three agricultural regions (northern, NAR; central, CAR; southern, SAR).

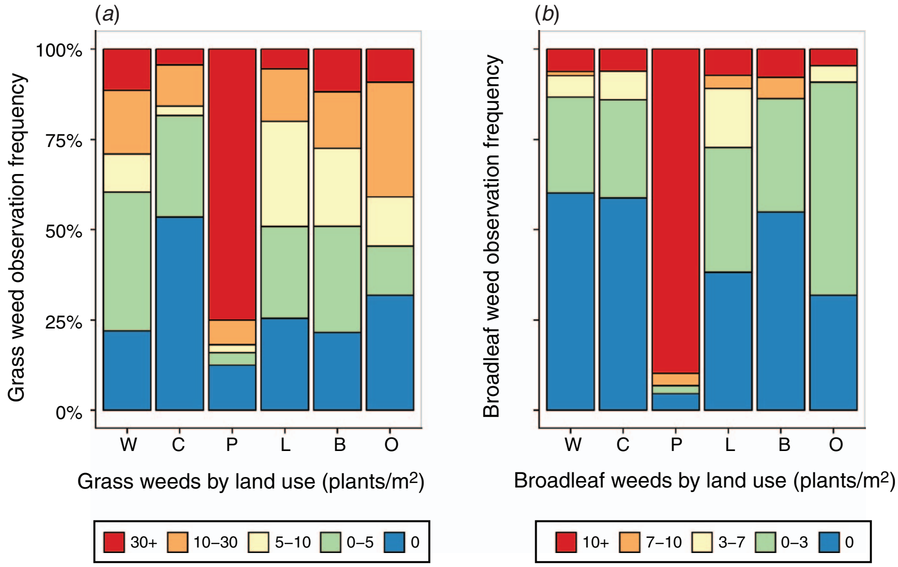

Fig. 3. Frequency of crop weed occurrence at anthesis, by density categories and land use for (*a*) grass weeds and (*b*) broadleaf weeds (W = wheat, C = canola, P = pasture, L = lupin, B = barley, O = other).

Table 1. Mean density (number/m²) of grass and broadleaf weeds in autumn and spring by land use and region (northern, central and southern agricultural regions)
Note: Values in parenthesis are s.e.m.

Land use or region	Grass weeds (%)			Broadleaf weeds (%)		
	Autumn	Spring	Spring vs Autumn	Autumn	Spring	Spring vs Autumn
Barley	22.4 (5.3)	13.2 (3.3)	59.0	7.2 (2.4)	3.6 (1.4)	49.2
Canola	25.3 (5.2)	7.1 (2.8)	28.2	3.4 (1.0)	2.0 (0.5)	59.4
Lupin	20.2 (4.7)	8.0 (1.7)	39.8	5.6 (2.0)	3.8 (1.3)	67.3
Other	29.7 (8.7)	20.6 (10.3)	69.3	5.3 (2.4)	2.9 (1.9)	55.3
Pasture	82.8 (52.0)	561.9 (80.7)	678.5	562.5 (477.1)	1160.9 (149.4)	206.4
Wheat	10.4 (1.2)	14.4 (3.0)	139.4	8.0 (1.2)	2.6 (0.4)	32.2
NAR	15.9 (2.7)	24.6 (8.2)	154.8	6.8 (2.0)	51.6 (21.3)	754.3
CAR	9.2 (1.4)	49.2 (17.7)	536.8	25.9 (19.8)	175.5 (48.1)	677.8
SAR	30.5 (3.8)	225.4 (39.3)	739.1	13.5 (2.5)	245.1 (46.5)	1812.9

mean weed density was 19.1 (±1.3, median 5), grass weeds 14.2 (±1.2, 2) and broadleaf weeds 4.9 (±0.5, 0.1) plants/m².

Weed density observed in spring compared with autumn depended on land use and weed species (Table 1). Grass weed density increased from autumn to spring in pasture and wheat; while decreasing for barley, canola and lupin (Table 1). Broadleaf weed density increased from autumn to spring in pasture, and decreased compared with autumn levels for all the crops (Table 1). Additionally, two canola herbicide tolerance types were grown, glyphosate tolerant (GT) and triazine tolerant (TT). GT cultivars were sown into paddocks with fewer autumn weeds, (P = 0.017) (23 plants/m², ± 12), compared with TT cultivars (52 plants/m², ± 11/m²) and in spring there were fewer grass weeds/m² in GT with 4/m², than TT with 17/m²; however, this was not statistically significant (P = 0.203).

Regional differences in weed density were large with means of 47, 122 and 259 plants/m² for the NAR, CAR and SAR respectively. Pairwise comparisons indicated fewer weeds in the NAR than CAR (P = 0.011) and SAR (P < 0.001) and fewer weeds in the CAR than the SAR (P < 0.001) (Fig. 4). Excluding pastures, mean total weeds/m² were 11, 17 and 41 for the NAR, CAR and SAR: the NAR and CAR not different (P = 0.077), both with fewer weeds than the SAR (P < 0.001). Excluding pastures, mean, grass weeds/m² were 7, 13 and 30 for the NAR, CAR and SAR: fewer grass weeds in the NAR than CAR (P = 0.016) and SAR (P < 0.001) and fewer weeds in the CAR than the SAR (P < 0.001). Excluding pastures, broadleaf weeds/m² were 4, 3 and 11 for the NAR, CAR and SAR: the NAR and CAR not different (P = 0.370), both with fewer broadleaf weeds than the SAR (P < 0.001). By crop there were differences in weed density

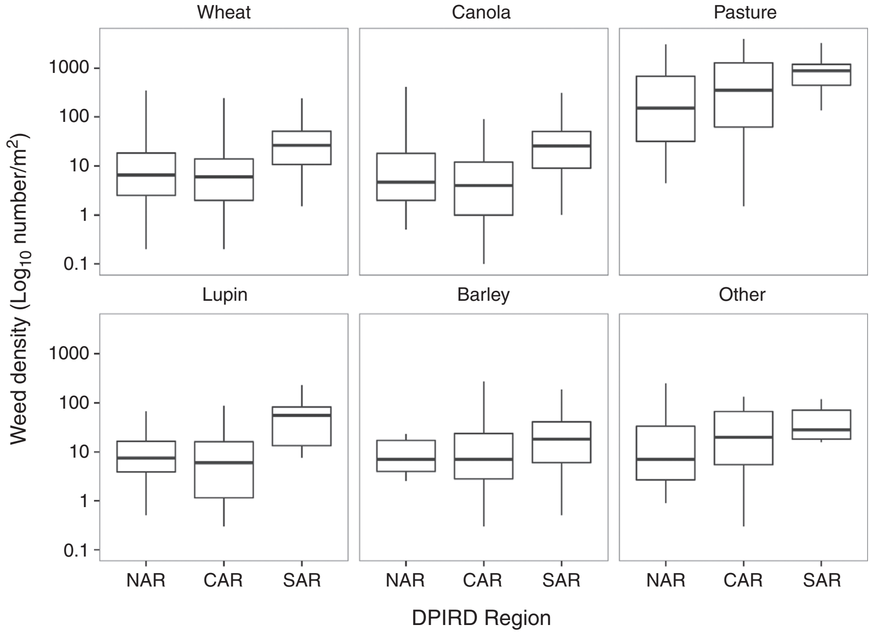

Fig. 4. Density of crop weeds across DPIRD regions (northern, central and southern agricultural regions) by land use, lower, middle and upper lines of boxes are the 1st quartile, median and 3rd quartile, respectively, whiskers extend 1.5 times interquartile range.

between regions ($P < 0.001$). For lupin and wheat the NAR and CAR had fewer weeds/m^2 than SAR ($P < 0.001$). For canola the NAR and CAR had fewer weeds/m^2 than SAR ($P < 0.05$). For barley there were no statistically significant differences in weed density between regions ($P = 0.417$).

Herbicides

Frequency of use

Overall there were 6.3 herbicide applications per paddock-year. The number of herbicides applied to each land use was not proportional to frequency of land use (χ^2 <0.001). A greater number of herbicides were applied to barley (7.4 ± 0.3), canola (5.6 ± 0.2), lupin (7.6 ± 0.5) and wheat (6.8 ± 0.1) compared with pasture (2.7 ± 0.2). Some herbicides were applied twice in the same year such that a mean of 5.6 active ingredients were applied/paddock.year; barley (6.6 ± 0.3), canola (4.5 ± 0.2), lupin (6.7 ± 0.3), wheat (6.2 ± 0.1) and pasture (2.5 ± 0.2). Overall, there were 2.7 tank mixes/paddock.year. There were differences between some of the crops, barley (3.1 ± 0.1), canola (3.3 ± 0.1), lupin (3.7 ± 0.2), wheat (2.6 ± 0.1) and a greater number of tank mixes were applied to crops compared with pasture (1.8 ± 0.1). Forty-five unique herbicide active ingredients were applied (Fig. 5). Of 3903 herbicide applications within the dataset, glyphosate was applied most frequently (15%), followed by trifluralin (10%), MCPA (9%), paraquat (7%) and triasulfuron (7%). Median amount of these herbicides applied (g a.i./ha.year) was 495 (interquartile range 450–675), 864 (720–960), 240 (180–300), 200 (135–250) and 12 (6–26) respectively. See Supplementary Material fig. S1 for more details.

The most frequently applied active ingredients differed by land use. For wheat, these were glyphosate, trifluralin, MCPA

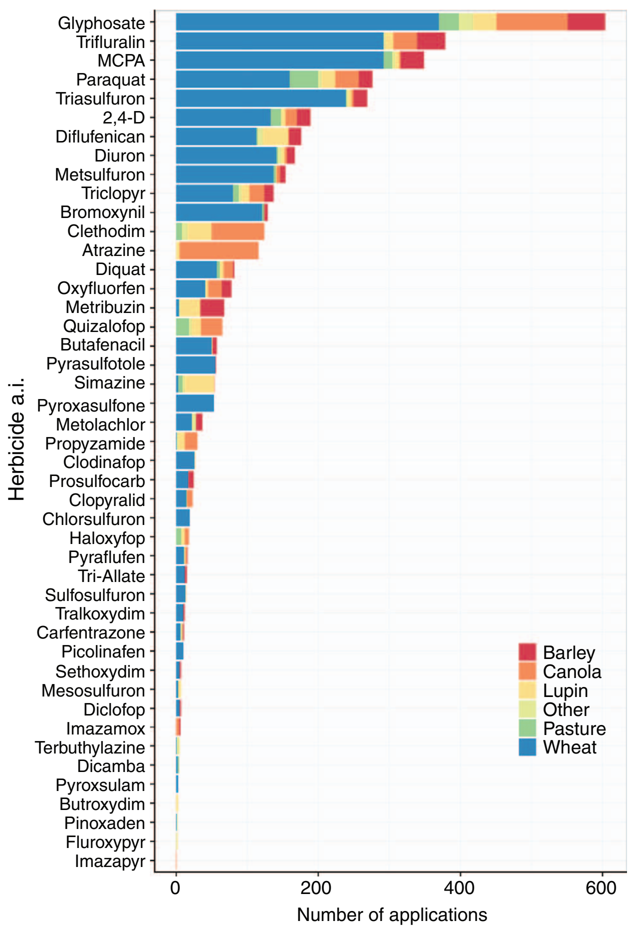

Fig. 5. Frequency of herbicide a.i. application by land use across 614 paddock-years from 2010 to 2014.

and triasulfuron at 1.0, 0.8, 0.8 and 0.7 applications/crop.year (including any fallow period) respectively. For canola, these were atrazine, glyphosate, clethodim and trifluralin at 1.2, 1.1, 0.8 and 0.4 applications/crop.year. For barley, these were glyphosate, trifluralin, metribuzin and MCPA at 1.2, 1.0, 0.8 and 0.8 applications/crop.year. For lupin, these were simazine, diflufenican, clethodim and glyphosate at 1.2, 0.9, 0.9 and 0.8 applications/crop.year. For pasture, these were paraquat, glyphosate, quizalofop and 2,4-D at 0.7, 0.5, 0.3 and 0.3 applications/paddock.year.

Timing of sowing and herbicide applications

Sowing occurred within a narrow window, 75% between Julian days 127 (7 May) and 148 (28 May). The median sowing date for all site-years was day 138 (18 May) with a standard deviation (s.d.) of 16 days. There were differences in sowing date between land uses ($P < 0.001$), canola and lupin sown at fewer Julian days (earlier) than each of the other land uses ($P \leq 0.004$). Median sowing dates were: Day 123 (3 May), s.d. 10 for canola; 126 (6 May), s.d. 12 lupin; 134 (14 May), s.d. 28 pasture; 138 (18 May), s.d. 17 other; and 142 (22 May) for barley and wheat, s.d. 13 and 12 respectively. There were differences in sowing date between years, 2010 and 2011 a greater number of days to sowing than 2013 and 2014 ($P < 0.001$). Median sowing date mostly decreased (earlier sowing) over the years: Day 145 (25 May), s.d. 10 in 2010; 139 (19 May), s.d. 14 in 2011; 141 (21 May), s.d. 15 in 2012; 134 (14 May), s.d. 21 in 2013; and 131 (11 May), s.d. 14 in 2014.

The timing of application of the four most used herbicides in relation to sowing date differed between land uses (Fig. 6). Notably for barley and wheat, glyphosate application almost always occurred before or on the day of seeding and paraquat was rarely used after sowing. For lupin, 12% of glyphosate and 53% of paraquat was applied more than 130 days after sowing. For canola, 42% of applications of glyphosate occurred between 100 and 1 day before sowing, 16% occurred on the day of sowing, 33% between sowing and 100 days after sowing and 9% more than 130 days after sowing, whereas 25% of paraquat was applied more than 130 days after sowing. For pasture, no trifluralin was applied while 47% of glyphosate and 76% of paraquat applications occurred more than 100 days after the first rainfall event of autumn. Monthly temporal patterns for the four most frequently used herbicides are available in Supplementary fig. S2.

Diversity of herbicide use

There was a high level of diversity of herbicide use, with 369 unique herbicide combinations applied, the top 25 given in Table 2. The four most frequent spray applications were single herbicides each with one a.i. (glyphosate, clethodim, paraquat and atrazine). Glyphosate was the herbicide used most frequently as a single product (19.5% of applications). It was used as a single product in canola more often than the other crops or pastures. For example, 46 of 100 applications of glyphosate to canola (Fig. 5) were as a single product (Table 2), compared with 40 of 369 applications to wheat. The number of unique herbicide mixes used per paddock.year differed by land use ($P < 0.001$), barley (3.0 $\pm$ 0.12), canola (3.0 $\pm$ 0.10), lupin (3.7 $\pm$ 0.17), other (2.9 $\pm$ 0.30), pasture (1.7 $\pm$ 0.10) and wheat (2.6 $\pm$ 0.05). Overall wheat received the most unique herbicide combinations and had the highest diversity of herbicides applied (Table 2). Table 2 also shows that the diversity of herbicides used was lower for pasture than other land uses.

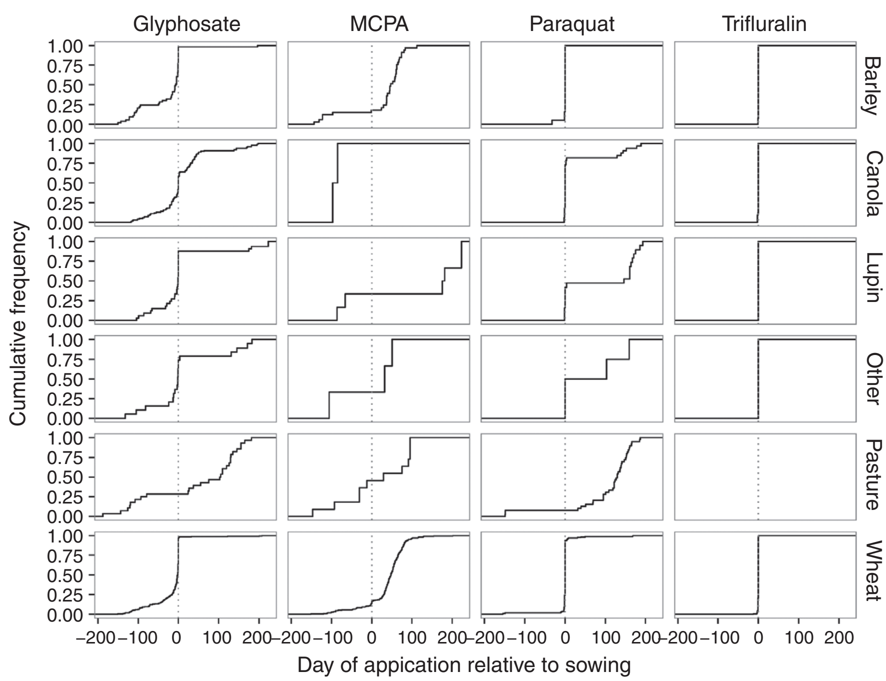

Fig. 6. Timing of application of the four most frequently used herbicides for each land use.

Table 2. Contingency table of herbicide mixtures applied by land use for the period 2010 to 2014

Herbicide active applied	Barley	Canola	Lupin	Other	Pasture	Wheat	Total
Glyphosate	5	46	4	5	17	40	117
Clethodim	0	41	15	3	0	0	59
Paraquat	0	7	7	2	28	5	49
Atrazine	0	47	0	0	0	0	47
2,4-D, glyphosate, triclopyr	4	10	3	2	2	20	41
Diflufenican, MCPA	8	0	0	1	0	30	39
Glyphosate, trifluralin	1	2	0	0	0	31	34
Diuron, paraquat, trifluralin	5	0	0	1	0	27	33
Clethodim, quizalofop	0	11	12	4	4	0	31
Glyphosate, oxyfluorfen	9	8	1	1	0	11	30
MCPA	4	0	0	0	1	23	28
Trifluralin	4	3	0	0	0	20	27
MCPA, triasulfuron	6	0	0	1	0	20	27
Glyphosate, triasulfuron, trifluralin	1	0	0	0	0	24	25
Diflufenican	2	0	13	4	0	5	24
2,4-D, glyphosate	3	0	0	0	6	15	24
Glyphosate, metsulfuron	2	1	0	1	0	18	22
2,4-D	4	0	0	0	1	16	21
Quizalofop	0	7	1	0	11	0	19
Diquat, paraquat, trifluralin	0	4	0	0	0	13	17
Bromoxynil, pyrasulfotole	0	0	0	0	0	17	17
Bromoxynil, diflufenican, MCPA	0	0	0	0	0	16	16
Bromoxynil, MCPA, pyrasulfotole	1	0	0	0	0	15	16
Glyphosate, MCPA, triclopyr	3	1	4	0	0	7	15
2,4-D, triclopyr	4	1	1	0	1	8	15
Total[A]	58	60	57	31	29	254	–
Shannon diversity index	3.75	3.21	3.57	3.27	2.67	4.91	–

[A]Total = sum of unique herbicide combinations within Focus Paddocks database.

Herbicide resistance

Of 663 annual ryegrass resistance tests, 200 (32%) were classified as resistant to the herbicide applied. Ryegrass seeds from 77% of paddocks survived maximum label rate of diclofop-methyl, 94% for triasulfuron, 5% for clethodim, 1% for trifluralin and 0% for atrazine and glyphosate. In the NAR, 34% of populations were classified as resistant, compared with 28% and 27% for the CAR and SAR respectively (Table 3). If a high proportion of populations were classified as resistant (>20% survivors at the recommended rate), the percentage of plants surviving was also high. For example, 97% of populations were resistant to diclofop-methyl in the NAR and this corresponded to 66% survival at the recommended rate (Table 3).

There was a poor correlation between the Mean survival percent (MS%), calculated from the resistance test, and annual ryegrass density in the field, calculated as the sum of annual ryegrass numbers from all years from the corresponding paddock, ($P = 0.68$, $r^2 = 0.01$) (Fig. 7*a*).

There were 53 instances when an a.i. was applied to a paddock with a population of annual ryegrass which tested resistant to that chemical. Forty six of these were triasulfuron; however, this herbicide was always applied in combination with a herbicide of a different mode of action. There were a further 194 applications of sulfonylurea herbicides (other than triasulfuron); 98% of these were applied in combination with another a.i. of a different mode of action.

Integrated weed management

Overall mean IWMI was 102 and it was higher in the NAR ($P < 0.001$), (122 ± 5) compared with CAR (83 ± 3) and SAR (92 ± 4), which were not different ($P = 0.336$). There were differences in IWMI by land use, canola greater than pasture, barley and wheat ($P < 0.001$, $P = 0.005$, $P = 0.006$ respectively) and lupin greater than pasture and barley ($P = 0.014$, $P = 0.034$). Mean IWMI for barley was 85 (±9), canola was 120 (±8), lupin was 116 (±10), other was 125 (±11), pasture was 84 (±8) and wheat was 101 (±3). There was no statistically significant relationship between IWMI and grass weed density in the following autumn (Fig. 7*b*). However, Chi-square analysis indicted a difference ($P = 0.002$) in the proportions of paddocks within weed density and IWMI categories. Paddocks with an IWMI <100 were three times more likely to have >75 grass weeds/m^2 the following autumn. IWM actions were summarised by land use (Table 4). Of these, the chemical options of the double knockdown and crop or pasture topping were most widely used. Whole-paddock burn and hay production occurred on <3% of paddocks (cereals only), grazing occurred on all pasture paddocks and >98% of cropping paddocks were sown using knife-point tillage.

Factors influencing weed numbers

Annual rainfall had the greatest influence on grass numbers in the following autumn (Fig. 8*a*), as expected in a rain-limited

Table 3. Percentage survival of annual ryegrass at half label/recommended rate (0.5 × R), full label rate (1.0 × R), and twice label rate (2.0 × R) of herbicide, in three agricultural regions (northern, central and southern agricultural regions) of south-west WA

Samples taken in the period 2010 to 2013. Note: Values in parenthesis () are s.e.m.; values in [] brackets are percent with >20% survivors or rated ≥2.5 at 1.0 × R

Region	Diclofop-methyl			Triasulfuron			Clethodim			Atrazine			Trifluralin			Glyphosate		
	0.5 × R	1.0 × R	2.0 × R	0.5 × R	1.0 × R	2.0 × R	0.5 × R	1.0 × R	2.0 × R	0.5 × R	1.0 × R	2.0 × R	0.5 × R	1.0 × R	2.0 × R	0.5 × R	1.0 × R	2.0 × R
NAR	65 (4.6)	66 [97] (6.5)	57 (6.1)	56 (2.8)	48 [100] (2.3)	55 (2.3)	10 (5.5)	4 [6] (3.6)	2 (2.8)	8 (0.7)	9 [0] (0.3)	9 (0.3)	10 (1.3)	4 [1] (1.7)	3 (1.3)	1 (0.6)	0 [0]	0
CAR	52 (5.7)	43 [69] (6.2)	43 (7.0)	47 (3.1)	41 [89] (3.3)	36 (4.0)	5 (3.7)	4 [7] (2.4)	2 (1.5)	4 (0.9)	5 [0] (0.9)	5 (0.9)	4 (0.8)	3 [0] (0.8)	1 (0.7)	2 (1.7)	0 [0]	0
SAR	41 (4.7)	40 [67] (5.3)	23 (5.0)	54 (2.4)	52 [95] (2.2)	50 (2.2)	0	0 [0]	0	8 (0.5)	7 [0] (0.6)	6 (0.6)	7 (0.6)	2 [0] (0.5)	1 (0.3)	1 (0.7)	0 [0]	0
All	53 (2.7)	50 (2.9)	41 (2.9)	53 (1.8)	47 (1.6)	47 (2.0)	5 (1.2)	3 (0.8)	1 (0.5)	7 (0.4)	7 (0.4)	7 (0.4)	7 (0.5)	3 (0.4)	2 (0.3)	1 (0.4)	0	0

environment. Weed density was higher when fewer herbicides were applied: 108 plants/m^2 with <5 herbicides and 35 plants/m^2 with ≥5 herbicides. A split occurred on crop type, with barley and wheat averaging 47 weeds/m^2 and the other land uses 12 weeds/m^2, (note no pastures received ≥5 herbicides). Barley and wheat split again based on herbicide resistance and number of herbicides applied (Fig. 8*a*).

With rainfall and pasture removed (Fig. 8*b*), region had the greatest influence on grass weed numbers in the following autumn, fewer weeds/m^2 in the NAR and CAR compared with the SAR. Within the SAR if <4.5 herbicides were applied weed density was 87 plants/m^2, which reduced to 26 plants/m^2 with ≥4.5 herbicides.

For ≥4.5 herbicides, a split occurred based on land use, wheat and barley averaging 33 weeds/m^2 compared with 11 weeds/m^2 across all other land uses. For the CAR and NAR there were three splits made on MS%, higher MS% did not always result in more weeds, and on IWMI with 85 weeds/m^2 (2% of the sample) when IWMI was <73 (Fig. 8*b*).

Discussion

Land use

Harries *et al*. (2015) discussed land use in detail. In brief, land use in the south-west of WA changed substantially over the past 15 years, with a trend towards increased cropping and reduced legume area due to increased wheat and canola production. The frequency and geographic distribution of land uses observed were consistent with industry statistics (Robertson *et al*. 2010; Borger *et al*. 2012; Harries *et al*. 2015; ABS 2016).

Weeds

Diversity of weeds (46 species) was lower than reported by Borger *et al*. (2012) from earlier surveys within south-west WA, which covered 956 sites recording 152 species. However, 128 species were observed at <1% of sites and the most common species were the same as our study including annual ryegrass, Cape weed and wild radish. Borger *et al*. (2012) reported changes in weed population and land use between 1997 and 2012 where the incidence of several species declined in cropped fields (i.e. silvergrass 25%, brome grass 20% and wild oat 18%) and across crop and pasture fields annual ryegrass incidence declined 17%. Overall, the proportion of fields cropped increased from 59 to 70%, a trend which continued within our survey at 85%. For annual ryegrass, Cape weed and wild radish, Borger *et al*. (2012) reported incidences of 84, 65 and 40% across all land uses compared with 64, 27 and 18% from our survey. Numerous studies of weed species richness in cropping systems report declining diversity associated with increased monoculture, simplification of rotations, adoption of minimum tillage and herbicides, lack of temporal variation in crop emergence, large field size and reduction of natural vegetation within the landscape (Baessler and Klotz 2006; Ulber *et al*. 2009; Gaba *et al*. 2010; Cirujeda *et al*. 2011; Nichols *et al*. 2015; Richner *et al*. 2015). Hence, declining species diversity in the survey zone is consistent with environmental limitations and recent trends in management

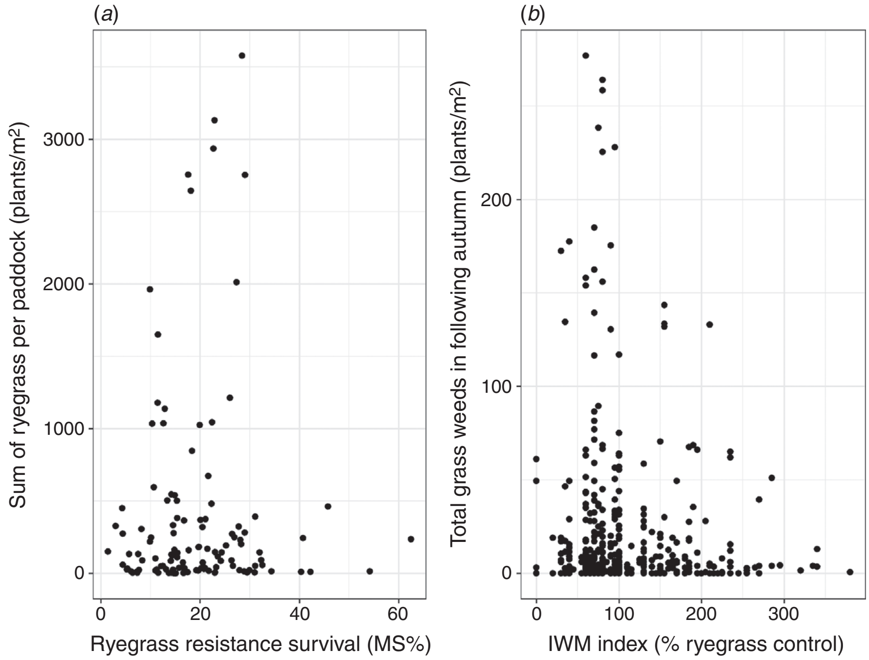

Fig. 7. Annual ryegrass numbers (plants/m^2) in the paddock compared with mean survival (MS%) in the resistance tests (*a*) and total grass weed numbers compared with integrated weed management (IWM) practices (*b*).

Table 4. Percentage of paddock-years with IWM action by land use from 2010 to 2014
L = low, M = med, H = high

	Till[A]	DK[B]	SSC[C]	SC[D]	Crop competition L	M	H
Barley	2	19	12	9	41	36	23
Canola	1	18	36	15	4	12	85
Lupin	3	10	38	14	7	36	57
Other	4	8	35	8	19	6	75
Pasture		14	53				
Wheat	7	19	12	13	25	40	34
Total	3	15	31	12	19	26	55

[A]Pre-sow tillage.
[B]Double knockdown.
[C]Seed-set control (crop or pasture-top or swath).
[D]Seed capture (chaff cart or windrow burn).

practices. Indeed we observed fewer species compared with several surveys of crop and pasture based agricultural landscapes within and outside Australia (Thomas 1985; Osten *et al*. 2007; Fried *et al*. 2008; Gaba *et al*. 2010; Pinke *et al*. 2012); although, Broster *et al*. (2012) found only 27 species in 192 cropping paddocks under a similar farming system to our survey in Eastern Australia. The reduction in weed species diversity may simplify weed management requirements, although this would depend on species composition.

Weed density was low in the majority of cropped paddocks, although slightly higher than reported by Llewellyn *et al*. (2009). Both studies suggest an intolerance by farmers of high weed populations in crops (i.e. large weed seedbanks) and weed density was a consideration when selecting land use. For example, wheat was sown into paddocks with fewer autumn grass weeds compared with canola. Additionally, GT canola cultivars were sown into paddocks with fewer autumn weeds than TT canola. This was due to GT canola being utilised more frequently in the northern and central regions (NAR 61%, CAR 39%, SAR 0%). Hence GT canola was employed on low weed seed banks as a component of IWM, rather than as a convenient method to control large weed populations. These results demonstrate that farmers were aware of the weed challenge and the likely control from each land use and adjusted land use accordingly. Indeed survey results from Llewellyn *et al*. (2016) indicated 66% of Western Australian farmers would grow more wheat if they did not have to consider weeds.

Herbicide resistance

The proportion of annual ryegrass populations resistant to all herbicides tested, except clethodim, were consistent with multiple surveys across southern Australia (Owen *et al*. 2007; Owen *et al*. 2014; Broster *et al*. 2019). For clethodim, the frequency of resistance was lower in our survey (5%) compared with 14 to 20% in other surveys (Owen *et al*. 2014; Broster *et al*. 2019). Geographic distribution was similar to other studies of annual ryegrass and other weed species, with higher levels of resistance in the NAR, associated with higher cropping and herbicide use intensity (Owen *et al*. 2007; Walsh *et al*. 2007; Owen and Powles 2009; Owen *et al*. 2014). Herbicide resistance was not associated with high weed density, similar to surveys in

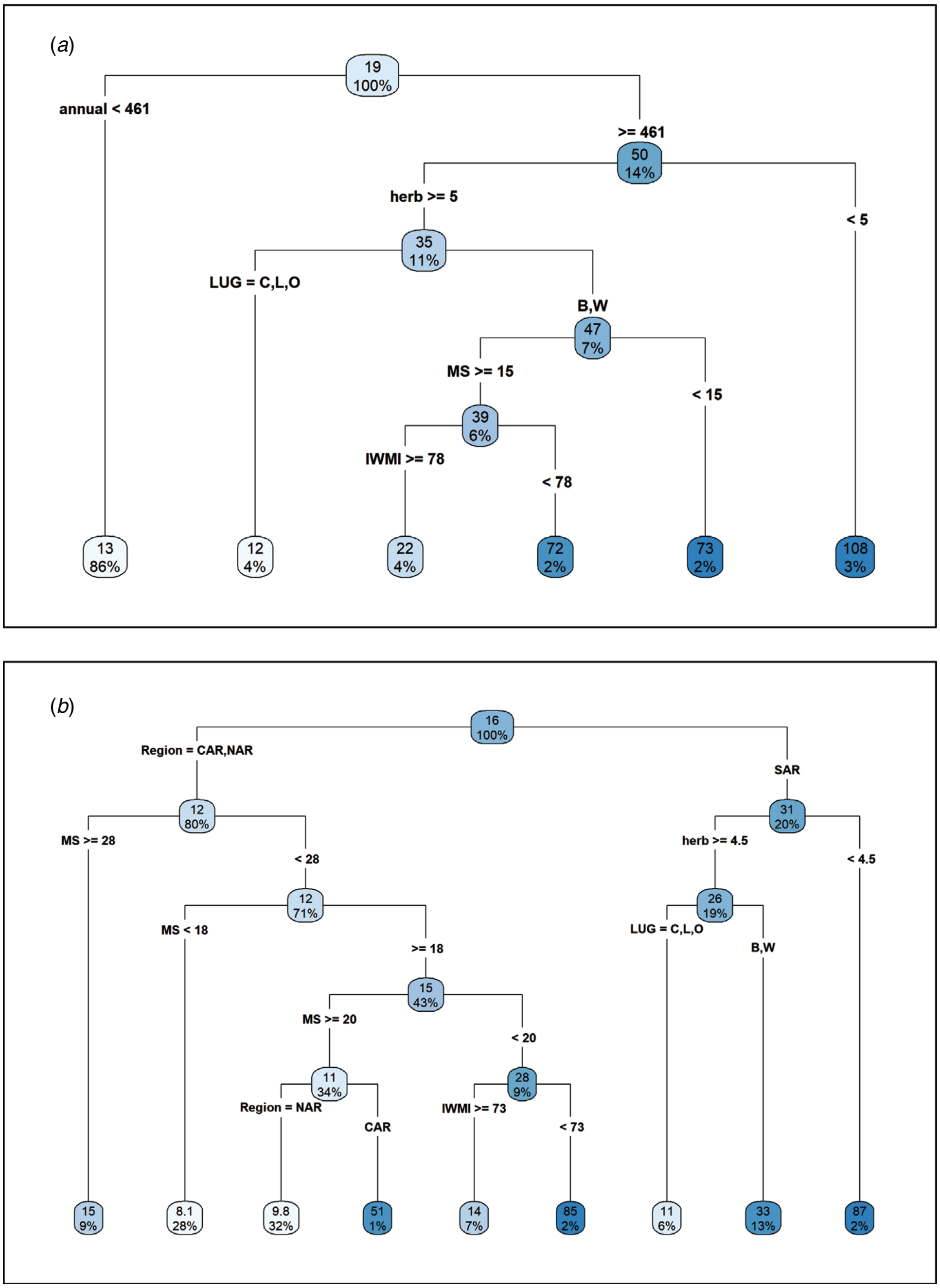

Fig. 8. Classification and regression tree analysis (CART) (*a*) including annual rainfall (annual) and pasture (P) and (*b*) excluding annual rainfall and pasture. The CART included region (northern, central and southern agricultural regions), mean herbicide resistance test survival (MS%), integrated weed management (IWM) index (IWMI), the number of herbicides used (herb) and land use group (LUG: B = barley, C = canola, L = lupin, O = other, W = wheat) as variates for predicting grass weed density/m^2 in the following autumn.

1998 and 2003 (Llewellyn *et al*. 2009), indicating farmers continue to effectively control increasingly resistant annual ryegrass populations.

The continued use of triasulfuron, which in most of cases is not effectively controlling annual ryegrass populations, may be warranted because it is a broad spectrum herbicide, registered to control 51 weed species in Australia. However, it is impossible to determine efficacy in the field as it is almost always applied in combination with another a.i. This uncertainty about the efficacy of triasulfuron needs to be balanced against the potential for carryover within soils and damage to subsequent broadleaf crop or pasture species, discussed in more detail below.

Herbicide use

Like the worldwide trend (Benbrook 2016), there has been increased herbicide use, particularly glyphosate, in WA, along with the uptake on no-tillage (Gill 1996). Despite the high frequency of herbicide resistance found in our survey there was a strong reliance on herbicides. This is consistent with conclusions of Walsh and Powles (2007), that herbicides remain the most efficient weed control technology for Australia's large cropping paddocks and reinforces the importance of preserving herbicide efficacy. In our study, there were fewer tank mixes and active ingredients applied to pastures than crop. Despite the high level of wheat production, there were few paddocks where continuous winter cereal cropping extended more than three seasons (Harries *et al*. 2015). The rotation of cereals with oilseeds, legumes and pasture phases provided opportunities for the use of multiple herbicide modes of action. Our results indicated a high diversity of herbicides were used (47 active ingredients) and their combinations/mixes (369) and doses. The use of herbicide mixtures was at least as prevalent as applications of single herbicides, suggesting that many growers were aware of herbicide resistance weed issues and were choosing to diversify their herbicide use in order to combat the development of herbicide resistant weed populations, in line with recent recommendations (Evans *et al*. 2016; Powles and Gaines 2016; Busi and Beckie 2019; Busi *et al*. 2019).

Despite the diversity of herbicide use, it was apparent that glyphosate, paraquat, pre-emergent herbicides (trifluralin, triasulfuron, diuron), Group 4, O herbicides (MCPA, 2,4-D, triclopyr) and Group 2, B herbicides (triasulfuron and metsulfuron) were the main herbicides used in this region. Newer herbicides, such as the pre-emergent chemical pyroxasulfone, have been adopted, although resistance to these is already developing (Brunton *et al*. 2019). There was almost double the number of glyphosate applications compared with the next most commonly used herbicide, which reflects worldwide trends in high glyphosate use intensity (Benbrook 2016). However, in contrast to global trends where an estimated 56% of glyphosate usage is within glyphosate tolerant crop production (Benbrook 2016), glyphosate application in the south-west of WA was predominantly associated with fallow weed control and pre-sowing weed control. The lifting of a moratorium on the production of genetically modified crops in 2011 in WA saw rapid adoption of GT canola to 20% of canola production area (~250 000 ha) by 2015 (Bucat *et al*. 2016), the majority within the NAR, to control weeds resistant to other herbicides. In 2011 Ashworth *et al*. (2015) surveyed 239 GT canola crops in WA, finding one population of wild radish and eight of annual ryegrass resistant to glyphosate. Neve *et al*. (2003) modelled the impact of increased selection pressure of GT canola predicting almost 100% of annual ryegrass populations becoming resistant to glyphosate after 20 years, particularly when reliance on glyphosate for pre-sowing weed control remained high. In comparison, resistance in a similar system using triazine tolerant canola resulted in 50% of populations exhibiting glyphosate resistance after 20 years. Hence, this analysis predicts use of GT canola is likely to reduce glyphosate sustainability. This has been documented by Evans *et al*. (2016) within glyphosate tolerant crops in North America, although model predictions from WA have not been validated.

Integrated weed management

The frequency of crop-topping and seed capture was similar to a previous survey of 132 Western Australian farmers, but the frequency of the double knockdown was lower, at 15% compared with 39% (Llewellyn and Pannell 2009). This is likely to be a function of late autumn rains in several seasons from 2010 to 2015, reducing the opportunity to delay sowing without incurring a high yield loss (Fletcher *et al*. 2015) and the trend towards earlier sowing in later years of the study, also documented by Fletcher *et al*. (2016). Double knockdown was utilised less in lupin than other crops, as expected given the early sowing date and the concentration of lupins in the northern region, where yield loss following delayed sowing is high (Harries *et al*. 2008). Tillage before sowing to stimulate weeds was rarely used (3% of paddock/years), nonetheless it was more common in wheat than the other crops. Again, this is likely to be due to sowing date differences, and fewer weed management options in spring in wheat compared with the lupin and canola. Seed set control with desiccant herbicides was used approximately three times more often in broad leaf crops, (~30%), compared with cereals and was used for 50% of pastures. Llewellyn *et al*. (2016) also reported many farmers were routinely crop topping (52% of farmers over 18% of their farm) and pasture topping (78% of farmers over 46% of their farm). This highlights that spring application of these herbicides is a key management tool to target weeds resistant to other herbicides and late germinating cohorts. In summary, land use dictated the IWM practices used and importantly the time within the year that these were applied. Increased dry sowing and variability of autumn rainfall are likely to reduce efficacy of autumn weed control. This will affect all land uses but may severely compromise those with few spring weed control options, such as cereals. Hence further development of weed seed management options at harvest is likely to become a key management strategy within WA grain production systems (Walsh and Powles 2007; Newman 2013; Walsh and Powles 2014) and will have varying levels of utility in other dryland farming systems, depending primarily on seed retention properties of dominant weed species (Owen 2016).

Relationships between land use, associated management practices and weeds

Our results show land use and weed density are linked. Land use selection was based around weed density and subsequent weed populations driven by the herbicides and integrated weed management options available within that land use. Despite the link between high cropping intensity and herbicide resistance in the NAR (Owen *et al*. 2007), the response has been to further increase cropping intensity compared with other regions, rather than diversify crop and pasture rotations. This was shown in our study by the poor pasture composition in the NAR, high frequency of non-selective herbicides applied to pasture in spring and relatively low weed density when wheat followed pasture. Additionally, greater use of cereals was accompanied by sulfonylurea herbicides, which have been associated with pasture decline (Heap 2000) and legume crop damage (Hollaway *et al*. 2006). Hence, in the NAR, four crops (wheat, barley, canola, and lupin) accounted for over 90% of land use and weeds were well controlled by strategically rotating these crops to ensure diversity of herbicides and IWM strategies that supressed weed seed production. Attempts are being made to increase crop and pasture diversity through integration of hard seeded pasture species to persist through IWM, sowing pastures in summer to accelerate re-establishment, and breeding pasture and crop legumes with improved tolerance to soil active herbicides applied in the crop phase (Heap 2000; Peck and Howie 2012; Rodda *et al*. 2016).

Conclusions

The results of this study suggest that the weed management methods being used are mostly effective, despite high levels of herbicide resistance. Land use has changed in order to manage herbicide resistant weeds, with pastures utilised less and crops with efficacious weed control options utilised more. Although this has been effective, there have been some unintended and possibly undesirable consequences of these land use changes. The most obvious of these has been a reduction in the utilisation and productivity of legume pastures and a transition from legume to oilseed crops. It is highly likely that these land use changes are affecting other biophysical variables that impact agricultural productivity and further investigation of this is required.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgements

This study was supported by the Western Australian Department of Primary Industries and Regional Development and the Grain Research and Development Corporation through projects DAW00213 and DAN00180. We acknowledge the support of the farmers who hosted Focus Paddocks, and staff from DPIRD, the Mingenew–Irwin Group, the Liebe Group, Western Australian No-tillage Farmers Association and the Facey Group who contributed to field monitoring and collation of farmer records.

References

ABS (2016) Agricultural commodities, Australia and state/territory: 2015–16, cat. no. 7121. Australian Bureau of Statistics. Available at: https://www.abs.gov.au/AUSSTATS/abs@.nsf/DetailsPage/7121.02015-16?OpenDocument (accessed 5 February 2020).

Anderson WK, Garlinge JR (2000) Crop management. In 'The wheat book: principles and practice'. (Eds WK Anderson, JR Garlinge) pp. 131–164. (Department of Agriculture Western Australia: Perth, WA, Australia)

Ashworth MB, Walsh MJ, Flower KC, Powles SB (2015) Identification of glyphosate-resistant *Lolium rigidum* and *Raphanus raphanistrum* populations within the first Western Australian plantings of transgenic glyphosate-resistant canola. *Crop & Pasture Science* **66**, 930–937. doi:10.1071/CP15031

Baessler C, Klotz S (2006) Effects of changes in agricultural land-use on landscape structure and arable weed vegetation over the last 50 years. *Agriculture, Ecosystems & Environment* **115**, 43–50. doi:10.1016/j.agee.2005.12.007

Benbrook CM (2016) Trends in glyphosate herbicide use in the United States and globally. *Environmental Sciences Europe* **28**, 3. doi:10.1186/s12302-016-0070-0

Borger C, Michael P, 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

Broster J, Pratley J (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 (2012) Weed species present in cereal crops in southern New South Wales. In '18th Australasian Weeds Conference'. Melbourne, Australia.

Broster JC, Pratley JE, Ip RHL, Ang L, Seng KP (2019) A quarter of a century of monitoring herbicide resistance in *Lolium rigidum* in Australia. *Crop & Pasture Science* **70**, 283–293. doi:10.1071/CP18584

Brunton DJ, Boutsalis P, Gill G, Preston C (2019) Resistance to very-long-chain fatty-acid (VLCFA)-inhibiting herbicides in multiple field-selected rigid ryegrass (*Lolium rigidum*) populations. *Weed Science* **67**, 267–272. doi:10.1017/wsc.2018.93

Bucat B, Seymour M, French B, Malik R, Sprigg S, Harries M, Stewart V (2016) Canola variety guide for Western Australia. Bulletin no. 4869, Department of Agriculture and Food, Perth, WA, Australia.

Bullock DG (1992) Crop rotation. *Critical Reviews in Plant Sciences* **11**, 309–326. doi:10.1080/07352689209382349

Busi R, Beckie H (2019) Herbicide resistance in focus paddocks of WA champion farmers. In 'Research updates'. (Ed. I Longson) (The Grains Industry of Western Australia: Perth, WA, Australia) Available at: https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2019/02/herbicide-resistance-in-focus-paddocks-of-wa-champion-farmers (accessed 5 February 2020)

Busi R, Vila M, Beckie H, Gaines T, Goggin D, Kaundun S, Lacoste M, Neve P, Nissen S, Norsworthy J (2013) Herbicide resistant weeds: from research and knowledge to future needs. *Evolutionary Applications* **6**, 1218–1221. doi:10.1111/eva.12098

Busi R, Powles SB, Beckie HJ, Renton M (2019) Rotations and mixtures of soil-applied herbicides delay resistance. *Pest Management Science* doi:10.1002/ps.5534

Chauhan B, Gill G, Preston C (2006) Tillage system effects on weed ecology, herbicide activity and persistence: a review. *Australian Journal of Experimental Agriculture* **46**, 1557–1570. doi:10.1071/EA05291

Cirujeda A, Aibar J, Zaragoza C (2011) Remarkable changes of weed species in Spanish cereal fields from 1976 to 2007. *Agronomy for Sustainable Development* **31**, 675–688. doi:10.1007/s13593-011-0030-4

Davis AS, Hill JD, Chase CA, Johanns AM, Liebman M (2012) Increasing cropping system diversity balances productivity, profitability and environmental health. *PLoS One* **7**, e47149. doi:10.1371/journal.pone.0047149

Derksen DA, Anderson RL, Blackshaw RE, Maxwell B (2002) Weed dynamics and management strategies for cropping systems in the northern Great Plains. *Agronomy Journal* **94**, 174–185. doi:10.2134/agronj2002.1740

Derpsch R, Friedrich T, Kassam A, Hongwen L (2010) Current status of adoption of no-till farming in the world and some of its main benefits. *International Journal of Agricultural and Biological Engineering* **3**, 1–25. doi:10.3965/j.issn.1934-6344.2010.01.001-025

Evans JA, Tranel PJ, Hager AG, Schutte B, Wu C, Chatham LA, Davis AS (2016) Managing the evolution of herbicide resistance. *Pest Management Science* **72**, 74–80. doi:10.1002/ps.4009

Fisher T, Hobbs P (2019) Tillage; global update and prospects. In 'Australian agriculture in 2020: from conservation to automation'. (Eds JE Pratley, J Kirkegaard) pp. 3–20. (Agronomy Australia and Charles Sturt University: Wagga Wagga, NSW, Australia)

Fletcher AL, Robertson MJ, Abrecht DG, Sharma DL, Holzworth DP (2015) Dry sowing increases farm level wheat yields but not production risks in a Mediterranean environment. *Agricultural Systems* **136**, 114–124. doi:10.1016/j.agsy.2015.03.004

Fletcher A, Lawes R, Weeks C (2016) Crop area increases drive earlier and dry sowing in Western Australia: implications for farming systems. *Crop & Pasture Science* **67**, 1268–1280. doi:10.1071/CP16200

French R, Seymour M, Malik R (2016) Plant density response and optimum crop densities for canola (*Brassica napus* L.) in Western Australia. *Crop & Pasture Science* **67**, 397–408. doi:10.1071/CP15373

Fried G, Norton LR, Reboud X (2008) Environmental and management factors determining weed species composition and diversity in France. *Agriculture, Ecosystems & Environment* **128**, 68–76. doi:10.1016/j.agee.2008.05.003

Gaba S, Chauvel B, Dessaint F, Bretagnolle V, Petit S (2010) Weed species richness in winter wheat increases with landscape heterogeneity. *Agriculture, Ecosystems & Environment* **138**, 318–323. doi:10.1016/j.agee.2010.06.005

Gianessi LP (2013) The increasing importance of herbicides in worldwide crop production. *Pest Management Science* **69**, 1099–1105. doi:10.1002/ps.3598

Gill G (1995) Development of herbicide resistance in annual ryegrass populations (*Lolium rigidum* Gaud.) in the cropping belt of Western Australia. *Australian Journal of Experimental Agriculture* **35**, 67–72. doi:10.1071/EA9950067

Gill G (1996) 'Management of herbicide resistant ryegrass in Western Australia-research and its adoption. In '11th Australian Weeds Conference'. Melbourne, Australia. (Weed Science Society of Victoria Inc.: Melbourne, Vic., Australia)

Harries M, French B, White P (2008) Crop establishment. In 'Producing lupins'. (Eds P White, B French, A McLarty) pp. 51–63. (Western Australian Department of Agriculture: Perth, WA, Australia)

Harries M, Anderson G, Hüberli D (2015) Crop sequences in Western Australia: what are they and are they sustainable? Findings of a four-year survey. *Crop & Pasture Science* **66**, 634–647. doi:10.1071/CP14221

Heap J (2000) Increasing *Medicago* resistance to soil residues of ALS-inhibiting herbicides. PhD thesis, Adelaide University, SA, Australia.

Heap I (2020) International survey of herbicide resistant weeds. Available at: www.weedscience.org (accessed 5 February 2020).

Hollaway K, Kookana RS, Noy D, Smith J, Wilhelm N (2006) Crop damage caused by residual acetolactate synthase herbicides in the soils of south-eastern Australia. *Australian Journal of Experimental Agriculture* **46**, 1323–1331. doi:10.1071/EA05053

Jeffrey SJ, Carter JO, Moodie KB, Beswick AR (2001) Using spatial interpolation to construct a comprehensive archive of Australian climate data. *Environmental Modelling & Software* **16**, 309–330. doi:10.1016/S1364-8152(01)00008-1

Kirkegaard J, Christen O, Krupinsky J, Layzell D (2008) Break crop benefits in temperate wheat production. *Field Crops Research* **107**, 185–195. doi:10.1016/j.fcr.2008.02.010

Kirkegaard JA, Peoples MB, Angus JF, Unkovich MJ (2011) Diversity and evolution of rainfed farming systems in southern Australia. In 'Rainfed farming systems'. pp. 715–754. (Springer: Berlin, Germany)

Lacoste M (2014) RIM 2013: default settings. Australian Herbicide Resistance Initiative and School of Agricultural and Resource Economics, Perth, WA, Australia. Available at: https://ahri.uwa.edu.au/wp-content/uploads/2015/12/RIM-2013-Default-settings_updated-Dec-2015.pdf (accessed 5 February 2020).

Llewellyn R, Ouzman J (2019) Conservation agriculture in Australia: 30 years on. In 'Australian agriculture in 2020: from conservation to automation'. (Eds JE Pratley, J Kirkegaard) pp. 21–33. (Agronomy Australia and Charles Sturt University: Wagga Wagga, NSW, Australia)

Llewellyn R, Pannell D (2009) Managing the herbicide resource: an evaluation of extension on management of herbicide-resistant weeds. *AgBioForum* **12**, 358–369.

Llewellyn R, D'Emden F, Owen M, Powles S (2009) Herbicide resistance in rigid ryegrass (*Lolium rigidum*) has not led to higher weed densities in Western Australian cropping fields. *Weed Science* **57**, 61–65. doi:10.1614/WS-08-067.1

Llewellyn R, D'Emden F, 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

Llewellyn R, Ronning D, Ouzman J, Walker S, Mayfield A, Clarke M (2016) 'Impact of weeds on Australian grain production: the cost of weeds to Australian grain growers and the adoption of weed management and tillage practices.' (Grains Research and Development Corporation and CSIRO: Canberra, ACT, Australia)

Neve P, Diggle AJ, Smith FP, Powles SB (2003) Simulating evolution of glyphosate resistance in *Lolium rigidum* II: past, present and future glyphosate use in Australian cropping. *Weed Research* **43**, 418–427. doi:10.1046/j.0043-1737.2003.00356.x

Newman P (2013) Focus paddocks – remaining weeds are hard to control. In 'Crop updates'. (Ed. I Longson) pp. 1–3. (Grains Institute of Western Australia: Perth, Western Australia) Available at: http://www.giwa.org.au/_literature_123725/Newman,_Peter_-_Focus_paddocks_-_remaining_weeds_are_hard_to_control (accessed 5 February 2019)

Nichols V, Verhulst N, Cox R, Govaerts B (2015) Weed dynamics and conservation agriculture principles: A review. *Field Crops Research* **183**, 56–68. doi:10.1016/j.fcr.2015.07.012

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Nichols RL, Webster TM, Bradley KW, Frisvold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: best management practices and recommendations. *Weed Science* **60**, 31–62. doi:10.1614/WS-D-11-00155.1

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 MDK (2016) Diverse approaches to herbicide-resistant weed management. *Weed Science* **64**, 570–584. doi:10.1614/WS-D-15-00117.1

Owen MJ, Powles SB (2009) Distribution and frequency of herbicide-resistant wild oat (spp.) across the Western Australian grain belt. *Crop & Pasture Science* **60**, 25–31. doi:10.1071/CP08178

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

Peck D, Howie J (2012) Development of an early season barrel medic (*Medicago truncatula* Gaertn.) with tolerance to sulfonylurea herbicide residues. *Crop & Pasture Science* **63**, 866–874. doi:10.1071/CP12130

Pinke G, Karácsony P, Czúcz B, Botta-Dukát Z, Lengyel A (2012) The influence of environment, management and site context on species composition of summer arable weed vegetation in Hungary. *Applied Vegetation Science* **15**, 136–144. doi:10.1111/j.1654-109X.2011.01158.x

Planfarm, Bankwest (2016) Planfarm Bankwest benchmarks 2015–16. Planfarm Pty Ltd and Bankwest Agribusiness Centre, Perth, WA, Australia. Available at: http://agric.firstsoftwaresolutions.com/attachments/1215/Planfarm%20Bankwest%20Benchmarks%202015-2016%20full-report.pdf (accessed 5 February 2020).

Powles SB, Gaines TA (2016) Exploring the potential for a regulatory change to encourage diversity in herbicide use. *Weed Science* **64**, 649–654. doi:10.1614/WS-D-15-00070.1

Rew L, Alston C, Harden S, Felton W (2000) Counts versus categories: choosing the more appropriate weed scoring method. *Australian Journal of Experimental Agriculture* **40**, 1121–1129. doi:10.1071/EA00079

Richner N, Holderegger R, Linder HP, Walter T (2015) Reviewing change in the arable flora of Europe: a meta-analysis. *Weed Science* **55**, 1–13. doi:10.1111/wre.12123

Robertson M, Lawes R, Bathgate A, Byrne F, White P, Sands R (2010) Determinants of the proportion of break crops on Western Australian broadacre farms. *Crop & Pasture Science* **61**, 203–213. doi:10.1071/CP09207

Rodda M, Rosewarne G, Sounness J (2016) Herbicide tolerant lentil varieties - a boost for reliable lentil production in Western Australia. In 'Research updates'. (Ed. I Longson) pp. 1–3. (The Grains Industry of Western Australia: Perth, Western Australia) Available at: http://www.giwa.org.au/_literature_209964/Rodda,_Matthew_et_al_-_Herbicide_tolerant_lentil_varieties_-_a_boost_for_reliable_lentil_production (accessed 5 February 2020)

Seymour M, Kirkegaard JA, Peoples MB, White PF, French RJ (2012) Break-crop benefits to wheat in Western Australia – insights from over three decades of research. *Crop & Pasture Science* **63**, 1–16. doi:10.1071/CP11320

Therneau, T, Atkinson, B (2019) rpart: recursive partitioning and regression trees. R package ver. 4.1–15. Available at: https://cran.r-project.org/web/packages/rpart/rpart.pdf (accessed 23 April 2020).

Thomas AG (1985) Weed survey system used in Saskatchewan for cereal and oilseed crops. *Weed Science* **33**, 34–43. doi:10.1017/S0043174500083892

Ulber L, Steinmann HH, Klimek S, Isselstein J (2009) An on-farm approach to investigate the impact of diversified crop rotations on weed species richness and composition in winter wheat. *Weed Research* **49**, 534–543. doi:10.1111/j.1365-3180.2009.00722.x

Walsh MJ, Powles SB (2007) Management strategies for herbicide-resistant weed populations in Australian dryland crop production systems. *Weed Technology* **21**, 332–338. doi:10.1614/WT-06-086.1

Walsh MJ, Powles SB (2014) Management of herbicide resistance in wheat cropping systems: learning from the Australian experience. *Pest Management Science* **70**, 1324–1328. doi:10.1002/ps.3704

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

Handling Editor: Christopher Preston