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An assessment of weed flora 14 years after the introduction of glyphosate-tolerant cotton in Australia

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Abstract. Glyphosate-tolerant (GT) cotton offers a multitude of benefits such as broad-spectrum and cost-effective weed control, simple weed management, and reduced impact on the environment. However, high adoption rates of GT cotton have led to overreliance on glyphosate in weed management and have decreased the use of other herbicide options and non-chemical weed-management strategies, possibly leading to the emergence of many resistant weeds. Previous surveys in 2006 and 2011 in the cotton-growing regions of New South Wales (NSW) and Queensland, Australia, indicated changes in weed populations over the period and increased prevalence of several weeds. These two surveys indicated increased dominance of *Conyza bonariensis*, *Echinochloa colona*, and *Chloris virgata* in these regions. Periodic weed surveys are necessary to assess weed population dynamics and shifts due to overreliance on glyphosate for weed management. A survey was carried out in the cotton-growing regions of NSW and Queensland in 2014–15, covering 135 fields. Survey results indicated the emergence of volunteer GT cotton as the most common weed present across all of the cotton-growing regions, occurring in 85% of fields, followed by *E. colona* (67% of fields surveyed), and *C. bonariensis* and *Sonchus oleraceus*, which were present in 51% of fields. The most prevalent grass weed after *E. colona* was *C. virgata* (37%). Broadleaf weeds *Ipomoea lonchophylla* and *Amaranthus mitchellii* were present in 40% and 37% of fields, respectively. Regional-level analysis indicated greater prevalence of *Sesbania cannabina* and *Parthenium hysterophorus* in Emerald region of Queensland. *Lolium rigidum* was present in the Griffith and Warren area of NSW during summer, even though it is a winter weed. The results of this study indicate integration of diversified weed-management options and inclusion of both non-chemical and chemical options because many major weeds observed in this study are tolerant to glyphosate and have already evolved resistance to glyphosate.

Additional keywords: GM crops, weed density, weed population shift.

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Introduction

In Australia, glyphosate-tolerant (GT) cotton (*Gossypium hirsutum* L.) has almost totally replaced conventional cotton varieties (ABCA 2015). This technology allows 'over-the-top' application of the highly efficacious herbicide glyphosate. Advantages of the GT trait in cotton include broad-spectrum weed control, simpler herbicide programs, more cost-effective weed management, greater safety to crops from herbicide damage, and lower impact on the environment (Webster and Sosnoskie 2010; Beckie 2011). However, the efficient weed control achieved by this technology has led to an overreliance on glyphosate by reducing other weed-management options (Werth *et al*. 2006, 2013; Webster and Sosnoskie 2010). Studies have indicated a clear reduction in usage of residual herbicides, shielded application of non-selective herbicides, and tillage as weed-control strategies with the introduction of GT cotton (Werth *et al*. 2006, 2013). Globally, intensive use of glyphosate has led to the emergence of several resistant weeds, and as a result, the initial success of GT crops has significantly declined in some regions (Sosnoskie and Culpepper 2014).

In Australia, a survey conducted in the cotton-growing regions of New South Wales (NSW) and Queensland in 2011 indicated the occurrence of many problem weeds (Werth *et al*. 2013). The two major weeds observed in the survey, *Conyza bonariensis* (L.) Cronq. and *Sonchus oleraceus* L., are hard to control with glyphosate (Werth *et al*. 2011). Abundant seed production, wind dispersal, and lack of dormancy allows *C. bonariensis* and *S. oleraceus* to spread further, and these weeds were expected to increase in prevalence in the future (Werth *et al*. 2011). Another major grass weed observed in this study was *Echinochloa colona* (L.) Link, a species highly adapted to cotton production across the world (Kruger *et al*. 2009; Prince *et al*. 2012; Riar *et al*. 2013; Werth *et al*. 2013). In addition, many glyphosate-resistant populations of *E. colona* have been observed in Australia (Preston 2015), indicating the potential of this weed to evolve glyphosate resistance rapidly under continued selection pressure. Another grass weed, *Chloris virgata* Sw., is also considered tolerant to glyphosate and four populations have been confirmed as resistant to glyphosate in Australia (Preston 2015).

Previous surveys in cotton-growing regions indicated a rapid shift in the weed populations (Charles *et al*. 2004; Werth *et al*. 2013). In 2001, *Ipomoea lonchophylla* J.Black was the number one weed, followed by *Hibiscus* sp. and *Cyperus rotundus* L. However, in 2008, *Hibiscus* sp. was the most common weed and *C. bonariensis* and *S. oleraceus* L. were second and third, respectively. These two weeds were not in the top 10 weeds of the 2001 survey (Charles *et al*. 2004; Werth *et al*. 2013). By 2011, *C. bonariensis* and *S. oleraceus* had become the first and second most common weeds and *C. rotundus* had reduced in prominence (Werth *et al*. 2013). In the 2011 survey, volunteer cotton was observed in 31% of fields surveyed. Previous studies indicated a clear and rapid shift in weed populations due to the enhanced selection pressure imposed by glyphosate, and the need for periodical surveys to assess the weed population dynamics and the emergence of weeds in the cotton-growing regions (Werth *et al*. 2013). Therefore, a survey was carried out in 2014–15 to identify the common weed flora in cotton-growing regions of NSW and Queensland.

Methods

The survey region extended from Emerald (23°31′0″S, 148°09′0″E) in Queensland to Griffith (34°17′24″S, 146°2′24″E) in NSW. Most of the cotton-growing areas in Australia are dominated by cracking clay soil referred to as Vertosols (Isbell 2002) or Vertisols (Soil Survey Staff 2014) (Table 1). The annual mean maximum and minimum temperatures and rainfall at the major survey sites are presented in Table 1.

In total, 135 fields were surveyed in NSW and Queensland. The survey locations were selected following consultation with CottonInfo officers of the Cotton Research Development Corporation (CRDC), Australia. The fields were in the Emerald (23), Darling Downs (22), and St George–Goondiwindi (20) regions of Queensland, and the Gwydir Basin (14), Namoi Basin (19), Warren (15), and Griffith (22) regions of NSW. Cotton planting is earliest in the Emerald region (mid-September) and

Table 1. Soil and weather data of the major survey sites

Soil data accessed from Australian Soil Resource Information System (ASRIS 2017); weather data accessed from Australian Bureau of Meteorology (Bureau of Meteorology 2017); n.a., not available. Values in parentheses: for temperature, mean of monthly temperature from planting to month of survey for each region; for rainfall, cumulative rainfall from one month before planting to survey time for each region

Survey region	Major sites in survey region	Soil type	Annual mean temperature (°C) Maximum	Minimum	Rainfall (mm)
St. George–Goondiwindi	St George	Clay	27.98 (34.63)	13.87 (19.10)	496 (89)
	North star	Clay	27.31 (33.40)	18.23 (15.95)	n.a. (111)
	Goondiwindi	Clay	27.23 (32.93)	12.81 (17.00)	598 (101)
	Boggabilla	Clay	28.13 (32.84)	12.21 (16.54)	n.a. (108)
Darling Downs	Bongeen	Clay	24.20 (32.40)	11.48 (16.47)	616 (117)
	Condamine	Clay	27.11 (28.30)	11.48 (15.80)	615 (113)
	Pittsworth	Clay	24.20 (31.23)	11.95 (16.10)	699 (120)
	Dalby	Clay	26.85 (32.40)	12.81 (16.46)	605 (112)
Emerald	Emerald	Clay	29.76 (31.77)	11.48 (16.63)	562 (106)
Griffith	Coleambally	Sandy clay loam	24.11 (30.53)	11.41 (14.50)	411 (121)
	Willbriggie	Sandy clay loam	23.60 (31.23)	10.10 (14.78)	404 (98)
	Darlington Point	Sandy clay loam	24.11 (30.55)	11.41 (12.93)	409 (99)
	Griffith	Sandy clay loam	23.90 (30.43)	10.08 (14.07)	406 (133)
Gwydir Basin	Ashley	Clay	26.13 (33.46)	9.34 (16.36)	569 (101)
	Rowena	Clay	27.66 (34.57)	12.63 (16.70)	506 (98)
	Moree	Clay	26.71 (33.50)	12.50 (17.10)	588 (118)
Namoi Basin	Narrabri	Clay	26.50 (33.40)	11.69 (16.50)	646 (105)
	Myall Vale	Clay	26.68 (33.23)	12.50 (16.35)	606 (115)
Warren	Nevertire	Sandy clay loam	24.61 (32.54)	10.80 (15.23)	464 (105)
	Trangie	Sandy clay loam	n.a. (29.96)	n.a. (12.84)	496 (98)
	Warren	Sandy clay loam	25.73 (32.27)	11.70 (15.00)	488 (121)

occurs progressively later in more southern areas, the latest planting being in the Griffith region (mid–late October). The survey began in November 2014 at Emerald and continued southwards to Griffith (January 2015), thereby minimising any differences in cotton growth stage during the survey.

The survey timing was after a minimum of two rounds of in-crop glyphosate applications. Because the 2014–15 cotton-farming season was affected by drought, only nine of 135 fields were under non-irrigated cotton. Therefore, the results were not analysed separately for non-irrigated cotton. The survey was conducted following the methodology of Walker *et al*. (2005) and Werth *et al*. (2013). Transects separated by ~50 m were surveyed. Twenty quadrats each 10 m by 1 m per field were used. Species density was rated on a 0–3 scale of number of weeds per 10 m^2: 0, no weeds; 1, 1–9 weeds; 2, 10–100 weeds; 3, >100 weeds. Percentage of fields with weed occurrence, density across all fields surveyed, and density rating in fields where the weed was present were determined.

Statistical analyses

Ten major weeds were selected based on occurrence (Table 2). A chi-square test was performed on presence and absence data. Analysis of variance (ANOVA) was performed on density across all the fields, and mean separation was carried out by Tukey–Kramer test. Data were not transformed before analysis because transformation did not improve the homogeneity of variance. Principal component analysis (PCA) was performed on weed density data for the 10 major weeds, and the components are presented for regions and 10 major weeds. Statistical analyses were performed using Minitab Version 16 (Minitab, State College, PA, USA: www.minitab.com).

Results

Volunteer GT cotton was the most common weed present across all cotton-growing regions (Table 2) and was present in 85% of fields. The next most common weed was *E. colona*, which was present in 67% of fields, followed by *C. bonariensis* and *S. oleraceus*, both present in 51% of fields. *Hibiscus trionum* var. *vesicarius* Hochr., a weed belonging to the same family as cotton, was present in 46% of the fields surveyed. The second-most prevalent grass weed across all the fields was *C. virgata*, which was present in 41% of the fields surveyed. *Ipomoea lonchophylla* and *Amaranthus mitchellii* Benth. were present in 40% and 37% of fields, respectively. *Physalis* sp. and *Portulaca oleracea* L. were present in only 34% and 22% of the fields surveyed. Notably, a previous major weed, *C. rotundus*, was present in only 19% of the fields surveyed (Charles 1995). The weed with the highest density rating across all fields surveyed was volunteer cotton (0.23), followed by *E. colona* (0.14), *C. virgata* (0.14), *C. bonariensis* (0.12), and *H. trionum* var. *vesicarius* (0.12) (Table 2).

The regional-level analysis indicated dominance of different weeds among regions (Tables 3 and 4). In the Emerald region, volunteer cotton, *C. bonariensis*, *C. rotundus*, *E. colona*, *H. trionum* var. *vesicarius*, and *Sesbania cannabina* (Retz.) Pers. were present in all fields (Table 3 and 4). The other common weeds were *A. mitchellii* (87%), *C. virgata* (96%), *Vigna radiata* (L.) R.Wilczek (91%), *Trianthema portulacastrum* L. (87%), and *S. oleraceus* (65%). Importantly, *Parthenium hysterophorus* L. was present in 56% of the fields surveyed.

Chloris virgata and volunteer cotton were the most common weeds occurring in the Darling Downs; these weeds occurred in 86% of fields. *Sonchus oleraceus*, *I. lonchophylla*, and *C. bonariensis* occurred in 68%, 64%, and 59% of fields surveyed in the Darling Downs, respectively. *Echinochloa colona* was present in 27% of fields surveyed in this region. In the St George–Goondiwindi region, volunteer cotton was present in 75% of the fields surveyed. *Sonchus oleraceus* (50%), *C. virgata* (45%), *I. lonchophylla* (45%), *Sida* sp. (45%), *E. colona* (40%), and *C. bonariensis* (30%) were the other common weeds present in the area.

In the Namoi region, volunteer cotton was present in 74% of the fields surveyed, followed by *Chloris truncata* R.Br. and *E. colona* (53%). *Portulaca oleracea* and *H. trionum* var. *vesicarius* were present in 42% of fields. *Sonchus oleraceus*, *Polygonum aviculare* L., and *C. bonariensis* were present at 42%, 33%, and 26% of fields, respectively.

In the Gwydir region, the most common weeds present (% of surveyed fields) were volunteer cotton (100%), *E. colona* (64%), *I. lonchophylla* (57%), *Cullen tenax* (Lindl.) J.W.Grimes (57%) and *S. oleraceus* (43%). In the Warren region, volunteer cotton was present in 80% of fields, followed by *Convolvulus erubescens* Sims. and *H. trionum* var. *vesicarius* in 67% of fields, and *C. truncata* in 60% of fields. *Echinochloa colona* was present in 47% of the field surveyed.

In the Griffith region, *E. colona* was present in 95% of fields surveyed. This was followed by volunteer cotton, in 73% of the fields surveyed, then *C. bonariensis* (59%), *S. oleraceus* (55%), *H. trionum* var. *vesicarius* (50%), and *P. oleracea* (45%). *Lolium rigidum* Gaud. was present in the Griffith region in 40% of the fields surveyed. Although *L. rigidum* is a winter weed, it was present in the cotton crop during summer, and seedset was noticed in farms.

The analysis of occurrence (chi-square test) of weeds indicated that volunteer cotton, *S. oleraceus* and *P. oleracea* were present uniformly between the regions (Table 3). The highest incidences of *C. bonariensis*, *H. trionum* var. *vesicarius*, *C. virgata*, *A. mitchellii*, and *Physalis* sp. were in the Emerald Region (Table 3). *Chloris virgata* was not observed in the Gwydir and Namoi regions. Maximum occurrence of *I. lonchophylla* was in the Darling Downs region. Analysis of density of the 10 major weeds indicated that *S. oleraceus* and *I. lonchophylla* were at maximum density in the Darling Downs (Table 4). The densities of volunteer cotton, *H. trionum* var. *vesicarius*, *C. virgata*, *A. mitchellii*, and *Physalis* sp. were highest in the Emerald region. *Conyza bonariensis* and *E. colona* were at highest density in the Griffith and Emerald regions. No significant difference was observed for the density of *P. oleracea*.

The PCA, performed on weed density to understand the variability, showed that the first three components accounted for 61% of variability (Fig. 1). The 3-dimensional plot with the principal components (PC1–3) indicated that survey sites are mostly clustered, although Emerald and Darling Downs tend to separate from the other regions slightly (Fig. 1*a*, *b*). These regions tend to separate owing to the high density of *C. virgata* present (Table 3). Among the weeds, *I. lonchophylla* was present in all

Table 2. Weed species, percentage of fields infested, and mean density rating from 135 fields surveyed

Species	Fields infested (%)	Density rating: Across all fields surveyed	Density rating: In fields where weed present
Volunteer cotton	85	0.230	0.31
Echinochloa colona (L.) Link	67	0.143	0.22
Conyza bonariensis (L.) Cronq.	51	0.116	0.23
Sonchus oleraceus L.	51	0.096	0.19
Hibiscus trionum var. *vesicarius* Hochr.	46	0.115	0.25
Chloris virgata Sw.	37	0.140	0.34
Ipomoea lonchophylla J.Black	40	0.108	0.27
Amaranthus mitchellii Benth.	37	0.078	0.21
Portulaca oleracea L.	37	0.092	0.25
Physalis sp.	21	0.037	0.21
Sesbania cannabina (Retz.) Pers.	20	0.116	0.58
Tribulus micrococcus Domin.	19	0.049	0.25
Cyperus rotundus L.	19	0.038	0.21
Trianthema portulacastrum L.	18	0.096	0.53
Cajanus cajan (L.) Millsp.	16	0.037	0.23
Rapistrum rugosum (L.) All.	16	0.029	0.18
Vigna radiata (L.) R.Wilczek	16	0.040	0.25
Chloris truncata R.Br.	16	0.032	0.21
Convolvulus erubescens Sims.	16	0.031	0.20
Sida sp.	16	0.025	0.16
Dactyloctenium radulans (R.Br.) P.Beauv.	13	0.032	0.24
Tribulus terrestris L.	13	0.024	0.19
Sorghum halepense (L.) Pers.	12	0.028	0.23
Neptunia gracilis Benth.	10	0.018	0.18
Parthenium hysterophorus L.	10	0.016	0.16
Helianthus annuus L.	9	0.018	0.20
Hibiscus trionum var. *trionum* L.	8	0.020	0.25
Abelmoschus ficulneus (L.) Wight	7	0.025	0.34
Cullen tenax (Lindl.) J.W.Grimes	7	0.009	0.13
Urochloa panicoides Beauv.	6	0.018	0.30
Amaranthus viridis L.	5	0.009	0.16
Digitaria ciliaris (Retz.) Koeler	5	0.004	0.09
Malvastrum coromandelianum (L.) Garcke	5	0.016	0.31
Phalaris paradoxa L.	5	0.003	0.06
Rhynchosia minima (L.) DC.	5	0.006	0.11
Xanthium spinosum L.	5	0.008	0.16
Chamaesyce drummondii (Boiss.) Hassall	4	0.010	0.23
Crotalaria dissitiflora Benth.	4	0.004	0.08
Datura sp.	4	0.007	0.16
Lithospermum arvense L.	4	0.004	0.09
Medicago sativa L.	4	0.007	0.16
Medicago polymorpha L.	4	0.009	0.20
Ibicella lutea (Lindl.) Van Eselt.	4	0.013	0.30
Polygonum aviculare L.	4	0.004	0.09
Anoda cristata (L.) Schlecht.	4	0.009	0.23
Citrullus lanatus (Thumb.) Matsum.&Nakai	4	0.004	0.12
Dinebra retroflexa (Vahl) Panz.	4	0.004	0.10
Lolium rigidum Gaudin.	4	0.006	0.16
Chenopodium sp.	3	0.007	0.23
Cynodon dactylon (L.) Pers.	3	0.005	0.16
Polymeria longifolia Lindl.	3	0.003	0.10
Sisymbrium thellungii O.E.Schulz	3	0.005	0.18
Vicia benghalensis L.	3	0.005	0.16
Amaranthus macrocarpus Benth.	2	0.007	0.32
Avena spp.	2	0.005	0.22
Boerhavia dominii Meikle&Hewson	2	0.008	0.37
Cyperus difformis L.	2	0.004	0.18
Echinochloa crus-galli (L.) P.Beauv.	2	0.004	0.17
Ipomoea plebeia R.Br.	2	0.002	0.10
Malva parviflora L.	2	0.003	0.15
Verbena aristigera S.Moore	2	0.001	0.05
Sorghum bicolor (L.) Moench	2	0.007	0.30
Argemone sp.	1	0.001	0.08
Bidens pilosa L.	1	0.001	0.10
Brassica napus L.	1	0.004	0.25
Cirsium vulgare (Savi) Ten.	1	0.001	0.05
Eragrostis spp.	1	0.006	0.38
Euphorbia davidii Subils	1	0.003	0.18
Lamium amplexicaule L.	1	0.001	0.10
Raphanus raphanistrum L.	1	0.004	0.25
Solanum nigrum L.	1	0.001	0.08
Trifolium sp.	1	0.004	0.30
Amaranthus hybridus L.	1	0.003	0.35
Atriplex sp.	1	0.002	0.25
Ageratum houstonianum Mill.	1	0.002	0.25
Digitaria sp.	1	0.001	0.05
Echinochloa sp.	1	0.001	0.15
Fallopia convolvulus (L.) A.Love	1	0.001	0.05
Fimbristylis dichotoma (L.) Vahl	1	0.001	0.15
Lactuca serriola L.	1	0.001	0.05
Panicum decompositum R.Br.	1	0.001	0.15
Polymeria pusilla R.Br.	1	0.001	0.05
Salsola kali L.	1	0.001	0.10
Solanum lycopersicum L.	1	0.002	0.25
Vigna lanceolata Benth.	1	0.001	0.20
Vicia monantha Retz.	1	0.001	0.20
Xanthium pungens Wallr.	1	0.001	0.05

regions, but at highest density in Darling Downs and the Gwydir Basin, whereas density was minimal in the Griffith region. The density pattern of *I. lonchophylla* made this weed conspicuous and different in distribution from the other weeds (Fig. 1*b*). Although detailed analysis of any variation due to soil, weather, and historical weed population dynamics between sites was not conducted, considerable similarity exists between the regions in terms of soil type, weather, cultivation practices, and herbicide usage (Table 1) (Werth *et al*. 2006, 2013).

Discussion

One of the major changes occurring in the cotton-growing regions of NSW and Queensland since the previous survey in 2011 is the increased presence of volunteer cotton. In the 2011 survey, volunteer cotton was not among the top 20 weeds (present in 31% of the fields surveyed); however, in the current survey, volunteer cotton emerged as the most widespread weed and was present in 85% of the fields surveyed (Table 2). Also noteworthy was the increased prevalence of *E. colona* and *C. virgata*. In the current survey, *E. colona* was in second position, compared with eighth position in the previous survey in 2011 (Table 5). In the previous survey, *C. virgata* was not listed among the top 10 weeds (Table 5). By contrast, *C. bonariensis* and *S. oleraceus* continued

Table 3. Occurrence (%) of 10 major weeds across the survey sites based on chi-square test
Within columns, values followed by the same letter are not significantly different ($P > 0.05$); n.s., not significant

	No. of fields surveyed	Volunteer cotton	*Echinochloa colona*	*Conyza bonariensis*	*Sonchus oleraceus*	*Hibiscus trionum* var. *vesicarius*	*Chloris virgata*	*Ipomoea lonchophylla*	*Amaranthus mitchellii*	*Portulaca oleracea*	*Physalis* sp.
St George–Goondiwindi	20	75a	40bc	30c	50a	5c	45b	45ab	25b	25a	5b
Darling Downs	22	86a	27c	59bc	68a	41b	86a	64a	36b	50a	9b
Emerald	23	100a	100a	100a	65a	96a	96a	61a	87a	13a	74a
Griffith	22	73a	95a	59bc	55a	50b	5c	5c	23b	45a	9b
Gwydir Basin	14	100a	64bc	0.0c	43a	21bc	29b	57a	21b	29a	0c
Namoi Basin	19	74a	53bc	26c	42a	42b	0.0c	26b	21b	42a	11b
Warren	15	80a	47bc	80b	20a	67b	0.0c	27b	20b	47a	0c
χ^2 ($P \le 0.05$)		11.9	42.3	50.9	11.3	42.6	84.1	25.2	33.6	10.5	61.0
P-value		n.s.	<0.001	<0.001	n.s.	<0.001	<0.001	<0.001	<0.001	n.s.	<0.001

Table 4. Weed density of 10 major weeds across the survey sites based on analysis of variance test
Within columns, values followed by the same letter are not significantly different ($P > 0.05$)

	No. of fields surveyed	Volunteer cotton	*Echinochloa colona*	*Conyza bonariensis*	*Sonchus oleraceus*	*Hibiscus trionum* var. *vesicarius*	*Chloris virgata*	*Ipomoea lonchophylla*	*Amaranthus mitchellii*	*Portulaca oleracea*	*Physalis* sp.
St George–Goondiwindi	20	0.15bc	0.07c	0.04b	0.06b	0.003c	0.05c	0.08bc	0.02b	0.04a	0.03b
Darling Downs	22	0.29b	0.07c	0.22a	0.19a	0.13bc	0.28b	0.26a	0.08b	0.15a	0.01b
Emerald	23	0.70a	0.28a	0.17ab	0.16ab	0.26a	0.48a	0.12abc	0.24a	0.04a	0.14a
Griffith	22	0.10c	0.23ab	0.12ab	0.11ab	0.10bc	0.01c	0.004c	0.04b	0.13a	0.02b
Gwydir Basin	14	0.14bc	0.06c	–	0.03b	0.03c	0.02c	0.20ab	0.02b	0.04a	–
Namoi Basin	19	0.11c	0.07c	0.05b	0.07ab	0.08bc	–	0.06bc	0.06b	0.11a	0.02b
Warren	15	0.13bc	0.10bc	0.22a	0.03b	0.19ab	–	0.02c	0.02b	0.14a	–

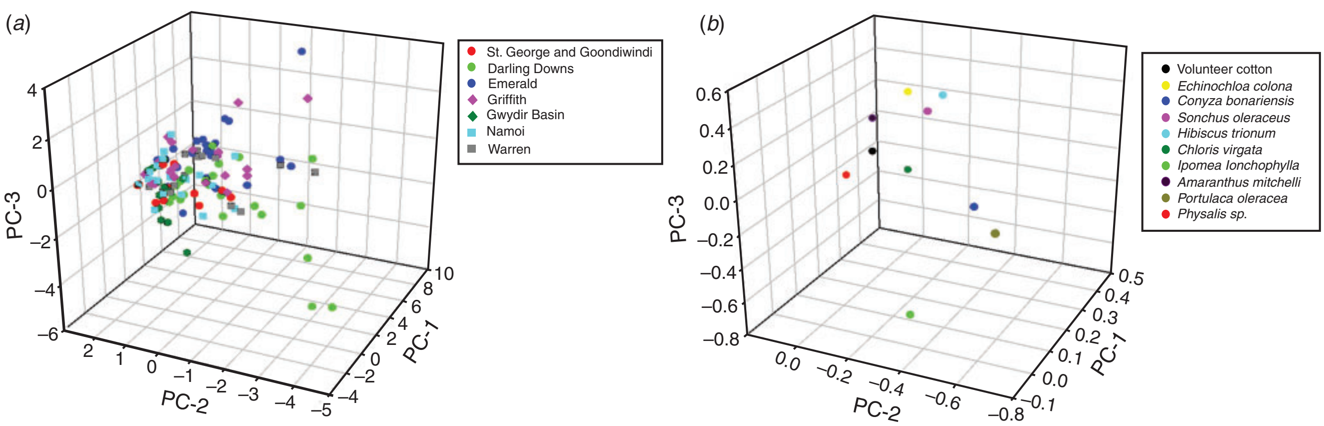

Fig. 1. Three-dimensional scatter plot showing three principal components of weed density (*a*) across the survey regions and (*b*) between weeds.

to be the dominant weeds in the region. Importantly, the major weeds *C. bonariensis*, *E. colona*, *S. oleraceus*, and *C. virgata* were assessed as having potential to evolve resistance to glyphosate rapidly from overreliance on glyphosate for weed management (Werth *et al.* 2011). There was a reduction in the incidence of *C. rotundus* over time. It was the third-most common weed species in 2001 and the seventh in 2008. In 2011 survey, *C. rotundus* was not among the top 10 weeds observed (Table 5).

Volunteer genetically modified crops are emerging as a major problem along with other herbicide-resistant weeds (McPherson *et al.* 2009; Dexter *et al.* 2010; Kumar and Jha 2015). Volunteer cotton was present as the seventh-most important weed in irrigated crops in the 2001 survey (Charles *et al.* 2004). This could be related to the introduction of GT cotton in 2000 and inexperience among growers in managing GT volunteers. By the 2008 survey, volunteer cotton was present in only 5% of surveyed fields (Werth *et al.* 2013), indicating better control of volunteer cotton by farmers. However, by the 2011 survey, there had been a rapid increase in the presence of volunteer cotton to 31% of fields surveyed

Table 5. Major 10 weeds in irrigated cotton based on previous surveys in 2001 (Charles *et al*. 2004) and in 2008 and 2011 (Werth *et al*. 2013)

Rank	2001	2008	2011
1	*Ipomoea lonchophylla* J.Black	*Hibiscus* sp.	*Conyza bonariensis* (L.) Cronq.
2	*Hibiscus* sp.	*Conyza bonariensis* (L.) Cronq.	*Sonchus oleraceus* L.
3	*Cyperus rotundus* L.	*Sonchus oleraceus* L	*Ipomoea lonchophylla* J.Black
4	*Echinochloa colona* (L.) Link	*Convolvulus erubescens* Sims.	*Convolvulus* sp.
5	*Rhynchosia minima* (L.) DC.	*Ipomoea lonchophylla* J.Black	*Amaranthus macrocarpus* Benth.
6	*Cullen cinereum* (Lindl.) J.W.Grimes	*Cullen* sp.	*Hibiscus* sp.
7	Volunteer cotton	*Tribulus* sp.	*Chamaesyce drummondii* (Boiss.) Hassall
8	*Physalis* sp.	*Cyperus* sp.	*Cullen* sp.
9	*Datura ferox* L.	*Echinochloa colona* (L.) Link	*Echinochloa colona* (L.) Link
10	*Neptunia gracilis* Benth.	*Fallopia convolvulus* (L.) A.Love	*Medicago polymorpha* L.

(Werth *et al*. 2013), possibly due to the (then) Australian-record cotton crop grown in 2010–11 (ABARES 2016). Volunteer cotton has not been reported as a major weed, and stewardship programs are in place to minimise the emergence of volunteer cotton and minimise the evolution of tolerant weeds (OGTR 2002; CottonInfo 2016). However, unlike canola (Simard and Legere 2004; O'Donovan *et al*. 2006; Baker and Preston 2008; Kumar and Jha 2015), cotton has been the subject of few studies on the dormancy and persistence of dispersed seeds as altered by tillage and management. The modern cultivars of cotton are typically devoid of dormancy (OGTR 2002). However, meaningful comparison is not possible for germination and dormancy characteristics between the seed material for planting and the dispersed seeds, because seeds for planting are acid delinted and processed (OGTR 2002). In the case of cotton, gene flow of resistance can only be through seed migration (Llewellyn and Fitt 1996; OGTR 2002), and a previous study and risk assessment indicated it is unlikely that volunteer cotton would emerge as a major weed problem under the prevailing management scenario (Eastick and Hearnden 2006). However, it would be highly advisable to ensure diversity in weed management and steps to minimise the migration of volunteer cotton to nearby cropping regions and agro-ecosystems.

Echinochloa colona was the second-most important weed across the cotton regions in 2014. This weed was at the ninth position in 2011, but it has increased in prevalence. It was assessed as a weed with potential to evolve resistance to glyphosate in the cotton-growing regions of Australia (Werth *et al*. 2011). In Australia, many populations of *E. colona* have been identified as glyphosate resistant (Preston 2015; Han *et al*. 2016; Nguyen *et al*. 2016), with most having been selected by repeated use of glyphosate in summer fallow rather than glyphosate application in cotton. However, given that glyphosate is also the main herbicide used in cotton, selection of resistance in summer fallows will lead to problems in cotton. There has been rapid resistance evolution in this weed under the current weed-management system that is solely reliant on glyphosate (Preston 2015).

The third and fourth weeds in terms of occurrence were *C. bonariensis* and *S. oleraceus*, respectively (Table 2). *Conyza bonariensis* is a difficult-to-control weed owing to its high reproductive potential, wind seed dispersal, and ability to evolve herbicide resistance (Wu *et al*. 2007; Walker *et al*. 2011). It was also rated as a high-risk weed for glyphosate-resistance evolution in cotton systems, and it exhibits a high level of tolerance to glyphosate (Werth *et. al.* 2011). These factors, combined with limited seed dormancy, favour this weed (Wu *et al*. 2007; Walker *et al*. 2011). Herbicide screening with glyphosate on 52 weed populations of *C. bonariensis* from north-eastern Australia indicated that resistance is prevalent in this weed (Walker *et al*. 2011). *Sonchus oleraceus* is also increasing in prevalence in the cotton-growing regions. This weed appeared in the surveys conducted in northern New South Wales (Walker *et al*. 2005), and since then, it has increased in prevalence in the subsequent surveys in this region (Werth *et al*. 2013).

Chloris virgata also increased in prevalence and emerged as the second-most dominant grass weed after *E. colona*, being present in 41% of the fields in this survey compared with 16% in 2011. *Chloris truncata* was present throughout the survey areas but was dominant in the Namoi region. Both of these weeds are C_4 plants and are highly adapted to the region. Both are difficult to manage with glyphosate and increasing in prevalence in cotton-growing regions. Already, several populations of *C. virgata* with tolerance to glyphosate have been identified in Australia (Preston 2015; Ngo *et al*. 2017), indicating the likelihood of rapid evolution of resistance through overreliance on glyphosate in weed management (Wakelin and Preston 2006; Preston *et al*. 2009; Fernando *et al*. 2016). *Amaranthus mitchellii* was the major weed observed belonging to the Amaranthaceae, a family that dominates the GT cropping systems of North America (Sosnoskie and Culpepper 2014; Evans *et al*. 2016). In North America, changes to weed populations have also occurred over time in cotton, similarly driven by the adoption of GT cotton. Culpepper (2006) reported increased problems with *Ipomoea* spp., *Commelina* spp. and *Amaranthus* spp. with the adoption of GT cotton in the southern USA, largely due to the reduction in tillage and overreliance on glyphosate. Webster and Sosnoskie (2010) also reported increases in *Ipomoea* spp. and *Commelina* spp. in Georgia, USA, and a decrease in *Senna* spp. By contrast, a survey of growers (Kruger *et al*. 2009) reported that most weed species had become less problematic or stayed the same with the adoption of GT cotton. In addition to changes in weed species, the overreliance on glyphosate in USA cotton production has resulted in rapid evolution of glyphosate-resistant weeds, most notably *Amaranthus palmeri* (Culpepper *et al*. 2006). Glyphosate-resistant *A. palmeri* has led to a substantial increase in weed-management costs for cotton in the USA (Webster and Sosnoskie 2010; Sosnoskie and Culpepper 2014). In Brazil, *A. palmeri* and *Amaranthus viridis* are common weeds in GT cotton and soybean crops (Carvalho *et al*. 2015) and *A. palmeri* has evolved resistance to glyphosate (Carvalho *et al*. 2015; Netto *et al*. 2016; Küpper *et al*. 2017).

Regional-level analysis indicated prevalence of *S. cannabina* and *P. hysterophorus* in the Emerald region. *S. cannabina* is a difficult to control weed with glyphosate. *Sesbania cannabina* is also present in St George area but at lower densities than in Emerald. Earlier reports indicated the presence of *P. hysterophorus* and the prevalence of *S. cannabina* in the Emerald region (Taylor *et al*. 2002). *Lolium rigidum* was an important weed in the Griffith and Warren regions. This is of concern because, although *L. rigidum* is a winter-dominant weed, it was present during summer in the cotton-growing regions of Griffith and Warren. In addition, *L. rigidum* is an outcrossing weed that has evolved widespread resistance to glyphosate (Preston *et al*. 2009), and that resistance spread can be rapidly through seed and pollen migration (Blanco-Moreno *et al*. 2004; Busi *et al*. 2008). Regionally, a high percentage of *C. rotundus* and *Cyperus difformis* L. was observed in the Griffith area.

The present study clearly indicated recent shifts in species importance in Australian cotton-production systems. Importantly, many of these species have also been assessed as weeds with high risk of evolving rapid resistance to glyphosate (Werth *et al*. 2011). Overreliance on glyphosate for both cotton production and fallow management in the cotton-growing regions over the past decade has precipitated the increase in incidence of these weed species. Continuing reliance on glyphosate for weed management in these regions will likely lead to an increase in the prevalence of these weeds and other weeds that evolve resistance to glyphosate (Werth *et al*. 2013). This makes it essential for farmers to adopt additional practices for weed management in cotton to deal with the emergence of glyphosate-resistant weeds (Thornby *et al*. 2013; Manalil *et al*. 2017). The cotton industry has promoted a strategy involving two non-glyphosate tactics in both the cotton crop and fallow to help manage glyphosate-resistant weeds (Thornby *et al*. 2013). Continued monitoring of the presence and abundance of weeds in cotton will provide essential information for fine-tuning weed-management strategies in cotton.

Conclusion

This survey indicates a shift in dominance of weeds in Australian cotton production compared with previous surveys carried out in the region. Most importantly, volunteer cotton has become more prevalent in cotton-production regions. In this study, volunteer cotton was present in 85% of fields surveyed, compared with 31% of fields in the previous survey in 2011. *Echinochloa colona* and *C. virgata* were the major grass weeds observed in this study and were present in 67% and 37% of the fields surveyed, respectively. *Echinochloa colona* was in ninth position in the survey of 2011, but it has increased in dominance to second position in this study, and *C. virgata* has increased in dominance from eighteenth to seventh position. *Conyza bonariensis* and *S. oleraceus* were the major broadleaf weeds observed in this study, and these weeds are likely to increase further in prevalence. These four weed species are particularly problematic because they have also evolved resistance to glyphosate in Australia. The trends identified in this study are of particular concern given the prevalence of GT cotton in Australian cotton production. The changing weed-species patterns identified in this survey demonstrate a need for changes to weed-management practices in cotton to deal with the changing weed flora.

Conflicts of interest

The authors declare no conflicts of interest.

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