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Weed species richness, density and relative abundance on farms in the subtropical grain region of Australia

L. J. Rew[A,F], *R. W. Medd*[B], *R. Van de Ven*[B], *J. J. Gavin*[A,C], *G. R. Robinson*[D], *M. Tuitee*[E], *J. Barnes*[E] *and S. Walker*[D]

[A]NSW Department of Primary Industries, Tamworth Agricultural Institute, Tamworth, NSW 2340, Australia.
[B]NSW Department of Primary Industries, Orange Agricultural Institute, Forest Road, Orange, NSW 2800, Australia.
[C]Present address: South Australian Department Water, Land and Biodiversity Conservation, PO Box 357, Port Augusta, SA, 5700, Australia.
[D]Department of Primary Industries, PO Box 2282, Toowoomba, Qld 4350, Australia.
[E]Primary Industries and Fisheries, PO Box 23, Kingaroy, Qld 4610, Australia.
[F]Corresponding author. Email: lrew@montana.edu

Abstract. Weed management is one of the most important economic and agronomic issues facing farmers in Australia's grain regions. Weed species occurrence and abundance was monitored between 1997 and 2000 on 46 paddocks (sites) across 18 commercial farms located in the Northern Grain Region. The sites generally fell within 4 disjunct regions, from south to north: Liverpool Plains, Moree, Goondiwindi and Kingaroy. While high species richness was found (139 species or species groups), only 8 species occurred in all 4 regions and many (56 species) only occurred at 1 site or region. No species were observed at every site but 7 species (*Sonchus* spp., *Avena* spp., *Conyza* spp., *Echinochloa* spp., *Convolvulus erubescens*, *Phalaris* spp. and *Lactuca serriola*) were recorded on more than 70% of sites. The average number of species observed within crops after treatment and before harvest was less than 13. Species richness tended to be higher in winter pulse crops, cotton and in fallows, but overall was similar at the different sampling seasons (summer *v.* winter). Separate species assemblages associated with the Goondiwindi and Kingaroy regions were identified by correspondence analysis but these appeared to form no logical functional group. The species richness and density was generally low, demonstrating that farmers are managing weed populations effectively in both summer and winter cropping phases. Despite the apparent adoption of conservation tillage, an increase in opportunity cropping and the diversity of crops grown (13) there was no obvious effect of management practices on weed species richness or relative abundance. *Avena* spp. and *Sonchus* spp. were 2 of the most dominant weeds, particularly in central and southern latitudes of the region; *Amaranthus* spp. and *Raphanus raphanistrum* were the most abundant species in the northern part of the region. The ubiquity of these and other species shows that continued vigilance is required to suppress weeds as a management issue.

Introduction

Weeds have been identified by farmers in all 3 major grain-growing regions of Australia as their single most important land management issue (Alemseged *et al*. 2001). One of these regions, the Northern Grain Region (NGR), covers the subtropical cropping areas of northern NSW, north of 32°S latitude, and Queensland. It has summer-dominant but variable rainfall, a hot climate and naturally fertile soils. The rainfall pattern provides the basis for both summer and winter crops to be grown in rotations (Webb *et al*. 1997). The environment favours an extensive weed flora with over 50 species listed as being a problem by farmers (Martin *et al*. 1988), while Felton *et al*. (1994) recorded over 100 species in a summer survey of commercial paddocks, and Wicks *et al*. (2000) recorded 80 weed species on 4 sites when comparing fallow management treatments.

Historically, growers in the NGR have predominantly used a bread wheat (*Triticum aestivum*)–sorghum (*Sorghum bicolor*) rotation, producing 2 crops in 3 years, with fallow periods varying from 6 to 18 months between crops. While this approach has provided reliable disease and weed control, it can result in wasteful water management (Hayman *et al*. 1996). Opportunity cropping, which involves sowing a crop whenever soil water reserves are adequate, has been suggested as a better alternative (e.g. Hayman *et al*. 1996). Consequently, farming systems in the region have diversified considerably with an increase in the range of summer and winter crops grown (Cooper 1999). Nevertheless, bread

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wheat remains the dominant winter crop and minor crops include other cereals [durum wheat (*Triticum durum*), barley (*Hordeum vulgare*) and oats (*Avena sativa*)], or grain legumes [chickpea (*Cicer arietinum*) and faba bean (*Vicia faba*)]. Alternatives to sorghum, the dominant summer crop, include dryland cotton (*Gossypium hirsutum*), sunflower (*Helianthus annuus*), maize (*Zea mays*) and the grain legumes [soybean (*Glycine max*), mungbean (*Vigna radiata*) and navy bean (*Phaseolus vulgaris*)]. Simultaneously with crop diversification, conservation tillage systems have been progressively replacing conventional tillage systems over the past 2 decades as the preferred soil preparation method. Provided crop and fallow management follow best practices, conservation tillage greatly increases grain yield through both better water storage and water use efficiency (Radford *et al*. 1995). Other advantages of these developments include increased profits, reduced risk of soil erosion, reduction in through-drainage of water for better salt management and the ability to better target specific weeds, such as *Avena* spp. or summer grasses, with more diverse herbicide options.

One disadvantage of the diversification of rotations and adoption of conservation tillage is the increased reliance on herbicides. Some herbicides have residual properties so, in order to ensure that future cropping choices are not restricted, herbicides have to be chosen carefully and with the aim of avoiding potential phytotoxic conflicts in subsequent crops (Jettner *et al*. 1999; Walker *et al*. 2000). A further concern with the increased reliance on herbicides to manage weeds both in the fallow and in-crop is the rising incidence of herbicide resistant weed populations in the region (Adkins *et al*. 1997; Storrie and Walker 1999; O'Donnell *et al*. 2002). This has lead to an increased emphasis on integrated weed management and the need for sustainable herbicide rotations to avoid heavy reliance on chemicals with similar modes of action.

Furthermore, the growth and maturation of weeds under the subtropical conditions is rapid. Many species have staggered recruitment patterns and this in conjunction with short life cycles increases the chances of weeds surviving to maturity and producing seeds. Limiting seed production of weed escapes is now recognised as a key goal of weed management programs (Jones and Medd 2000; Medd 1997), and adds emphasis to the planning of weed management programs and the timing of operations.

The study reported here arose from concerns about the increasing complexity of weed management in cropping systems in the NGR, and the realisation that a better understanding of the weed species and assemblages and associated control problems is needed to identify areas requiring future research. Previously, many weed studies in the NGR concentrated on fallow weeds and did not fully reflect the complexity of on-farm weed problems. The reported work had the objective of monitoring weeds on commercial paddocks in the NGR, through winter and summer cropping as well as fallow cycles for over 3 years, to obtain a better understanding of the weed species spectrum and abundance.

Materials and methods

Location of sites

Paddocks on 18 farms were monitored in 4 disjunct regions of the NGR, 8 on the Liverpool Plains (L), 3 south of Moree (M), 4 north of Goondiwindi (G) and 3 south of Kingaroy (K), from May 1997 until July 2000. These 4 disjunct regions of the NGR are referred to as regions hereafter. A total of 3 paddocks were sampled on each of the collaborating L and M properties, with 1 paddock in each part of the notional wheat–sorghum and long fallow rotation. The exception was 1 M farm where 4 paddocks were sampled. In the G region participating farmers followed a more continuous winter cereal regime, whereas a more opportunistic and multiple cropping regime was monitored on the participating K farms. A total of 2 paddocks per farm were sampled in the G region and on 1 of the K farms. At the 2 remaining K farms, only 1 paddock per farm was assessed. There was a total of 46 paddocks (sites) sampled overall. The L, M and G sites were located on predominately deep heavy grey vertisols (cracking clays) and the K sites on strongly structured red krasnozem or euchrozem soils.

Sampling scheme

At each site, parallel transects located 20 m apart were established. Each transect was 100 m long, with 4 permanent quadrats (10 × 1 m) placed at 20-m intervals along each transect. At the L and M sites 4 such transects were used (providing 16 quadrats), while only 3 transects were established at the G and K sites, giving 12 quadrats. To ensure accurate and easy repositioning of transects, distances from static landmarks (e.g. fence posts, trees) were generally recorded, along with grid coordinate readings from differential global positioning systems (DGPS, Magellan GPS Systems, Australia).

Weeds were identified and individual species densities assessed within each 10 m^2 quadrat using a scoring system involving 8 categories (Table 1). This involved visually estimating the density of each species within a quadrat and assigning it a score. A more detailed description of the scoring system and its validation is given by Rew *et al*. (2000). Species nomenclature follows the Flora of NSW (Harden 1990, 2002), and several handbooks were consulted to aid identification in the field.

Quadrats at all sites were assessed 2–3 times during the cropping phase; within 6–8 weeks of sowing (post-sowing) and again 1–3 weeks before harvest (pre-harvest). If post-emergence herbicides were applied to the crop, an assessment was made 4 weeks after application

Table 1. Scoring system used for estimating weed density of species observed within 10 m^2 quadrats and the assigned mid-range density value used in data analysis

Score category	Range (plants/10 m^2)	Mid-range density (plants/10 m^2)
0	0	0.0
1	1–6	3.5
2	7–20	14.5
3	21–60	40.5
4	61–190	125.5
5	191–600	400.5
6	601–6000	3300.0
7	>6000	10000.0

(post-emergent). The sites were also assessed before sowing (pre-sowing) and after harvest (post-harvest) whenever conditions promoted weed emergence.

Data collation and analyses

A database of information and records compiled by farm, paddock/site, region, year, season, crop species or fallow, tillage regime, sampling time, herbicide treatments, species occurrence and density categories facilitated the spatial and temporal collation and tabulation of crops grown and species richness over time.

Correspondence analysis (CA; ter Braak 1995) was used to analyse an aspect of the data, as this method has proven very useful in situations with high species turnover (high β diversity) over a large range of environmental conditions; exactly the situation observed in our field survey. With CA, it is assumed that species respond unimodally to underlying environmental gradients. That is, each species has an optimal position on a particular environmental gradient and responds less favourably further away from this optimum. For this study the CA was restricted to presence/absence data, forming a 139 weed species by 46 sites array with the (i, j) cell of the array ($i = 1, \ldots, 139$ and $j = 1, \ldots, 46$) taken as one if species i was observed at site j at least once during the survey, and zero otherwise.

Ordination techniques such as CA are a convenient way of summarising multivariate data into easy to interpret scatter diagrams or, more ambitiously, to uncover the underlying structure of the data (Jongman *et al*. 1995). In our analysis we also investigated, to an extent, the removal of rare species from the dataset as their inclusion may affect the ordination (Kenkel *et al*. 2002; McCune and Grace 2002). All CA analyses were performed in R (Ihaka and Gerileman 1996), a free, open source statistical environment, using the Vegan: Community Ecology Package (freely available at http://cc.oulu.fi/∼jarioksa/softhelp/vegan.html).

For analysis of species density and abundance the individual quadrat scores were converted into counts, replacing each species score in a quadrat with its approximate mid-range value, except for score values of 7 which were given a density of 10 000 (Table 1). Mean densities were then determined for each site at each sampling time, averaging over all quadrats. The relative abundance (r_{ab}), defined by Derksen *et al*. (1994), was then calculated for each species within each region separately. The relative abundance value (r_{ab}) gives an equally weighted measure of relative frequency and relative incidence. To calculate r_{ab} for a species (i) in a particular region let X_{ij} denote the mean density of species group i at site/sampling time j within the particular region and let Y_{ij} equal 1 if X_{ij} is greater than zero and 0 otherwise (i.e. Y_{ij} is an indicator variable). Then, the relative abundance (r_{ab}) of species group i for a particular region is calculated as:

$$r_{ab}(i) = \frac{1}{2}\left(\frac{\sum_j X_{ij}}{\sum_{ij} X_{ij}} + \frac{\sum_j Y_{ij}}{\sum_{ij} Y_{ij}}\right).$$

Here the summation is for all species (i) and all sites/sampling time (j) within the particular region. For each region the sum over species of the r_{ab} values equals 1 (i.e. $\sum_i r_{ab}(i) = 1$).

Results

Overall, 13 different crops were grown in the 46 sites spanning the 4 regions, though many were sown infrequently and not all were sampled (Table 2). Bread wheat was the most frequently sown winter crop followed by durum wheat. Sorghum was the most frequently sown summer crop.

At least 157 taxa were recorded across all the sites. Some species were grouped at a generic level due to difficulties in determining specific identification at the seedling stage. These are reported as genus followed by spp. for: *Avena fatua* and *A. ludoviciana*; *Echinochloa crus-galli* and *E. colona*; *Epilobium billardierianum* subsp. *cinereum* and *E. hirtigerum*; undetermined *Euphorbia* species and *Chaemsyce drummondii*; undetermined *Euchiton/Gamochaeta* species; undetermined *Lepidium* species and *L. bonariense*; *Medicago minima* and *M. polymorpha* var. *vulgaris* and undetermined *Medicago* species; *Polygonum aviculare* and *P. patulum*; *Sonchus asper* and *S. oleraceus*; *Sisymbrium officinale*, *S. orientale* and *S. thellungii*; and undetermined *Veronica* species and *V. peregrine*. Thirteen volunteer crops were recorded and included in the weed list, namely barley, chickpea, cotton, faba bean, maize, mungbean, navy bean, oats, sorghum, soybean, sunflower, bread wheat and durum wheat — the last 2 crops being grouped since they were difficult to distinguish. Including the unknown category, the resulting condensed list of 139 species or generic groups (Appendix 1), are hereafter referred to as species.

Table 2. Number of sites sown to different crops and sampled for weeds during May 1997–July 2000

Values in parentheses are sites sown to crops but not sampled for weeds in that year. Year represents the year in which the crop was sown but not necessarily harvested

Crop	1997	1998	1999
Winter crops			
Bread wheat	18	14	16
Durum wheat	4	5	6
Barley	3	1	2
Faba bean	1	0	2
Chickpea	1	0 (1)	1
Canola	1	0	0
Oats	0	1	0
Summer crops			
Sorghum	8 (4)	7 (3)	13
Mungbean	0	2	0
Soybean	0 (2)	1 (2)	1
Maize	0 (1)	1	2
Cotton	0	1 (1)	2
Navy bean	0	0	1

Species richness

Weed species diversity/richness for the entire study period was highest in L with 111 species, whilst 71 species were recorded at M, 62 in G and the least diverse was K with 27 species. In all regions the richness consisted of species that were recorded only in a region (56 species) or species that occured in 2 (43 species), 3 (32 species) or all 4 regions (8 species) namely: *Amaranthus* spp., *Avena* spp., *Lamium amplexicaule*, *Raphanus raphanistrum*, *Rapistrum rugosum*, *Sonchus* spp., *Urochloa panicoides* and volunteer wheat (durum and winter wheat were grouped) (Table 3).

Table 3. Species richness (number of species) recorded in each region (L, Liverpool Plains; M, Moree; G, Goondiwindi; K, Kingaroy) during May 1997–July 2000

The number of species occurring in a region is indicated in italics; where a species occurred in 2 or more regions it is included in each cell

	L	M	G	K	Total
Number of species recorded only in a single region	*33*				
		4			
			12		
				7	**56**
Number of species common to 2 regions	*24*	*24*			
	11		*11*		
	3			*3*	
		2	*2*		
		1		*1*	
			2	*2*	**43**
Number of species common to 3 regions	*26*	*26*	*26*		
	1		*1*	*1*	
	5	*5*		*5*	**32**
Ubiquitous species	*8*	*8*	*8*	*8*	**8**
Total	**111**	**70**	**62**	**27**	**139**

The mean number of species in any region for a site at any time was less than 10 and declined, as did variability, from south (L) to north (K), when averaged across sampling times (Fig. 1*a*). Species richness tended to be greater in winter pulse crops, cotton and fallows than other crops (Fig. 1*b*), and the richness of the weed floras recorded in winter was marginally greater and more diverse than that recorded in summer periods (Fig. 1*c*).

Similarly, species density was highly skewed and mostly below 17 plants/m^2 in L, M and G regions and mostly below 10 plants/m^2 in all crops (Fig. 1*d* and *e*). Mean density was $<$10 plants/m^2 in the M region, slightly higher in the L (14) and G (16) regions and about 52 plants/m^2 in the K region because of high densities in some bread wheat crops. Sorghum, cotton and the summer pulse crops tended to have lower weed densities than the other crops (Fig. 1*e*). Thus mean weed densities observed during the winter seasons were slightly higher than those recorded during summer (Fig. 1*f*).

Correspondence analysis — site and species separation

Eigenvalues of $\lambda_1 = 0.458$, $\lambda_2 = 0.345$, $\lambda_3 = 0.208$, $\lambda_4 = 0.189$ and $\lambda_5 = 0.176$ were calculated for the first 5 ordination axes of the CA, with the remaining eigenvalues declining slowly. Plots of the site scores for the first 2 axes of the CA clearly show separation of the regions into 3 distinct groups, LP/M, G and K (Fig. 2). The strong separation on these 2 axes into 3 regional groupings can be attributed in part to those species that are unique to a region or that occur infrequently. The corresponding plot of the species scores (Fig. 3) demonstrates this point; with species affiliated with the regional groupings, and with a number of species strongly affiliated to the K region and others to the G region over the LP/M region and *vice versa*.

However, ordination of species is not as clear as for the sites (Fig. 2 *v.* Fig. 3). Among those separated to the far right of the first ordination axis, 5 species were recorded only in the K region, but other species were recorded in a mixture of regions. The second axis separates some species into the bottom left corner, and 11 of those species were recorded solely in the G region. Another 11 species, which could be considered part of the same cluster, were recorded in a mixture of regions, which always included G, and 2 species that were recorded only in L region. The majority of species for the L and M regions show no separation on a species basis using correspondence analysis, indicating that there is a level of overlap in species occurrence and these species are mainly observed near the origin of the axes (Fig. 3). However, the tabular data reveals that 4 species were recorded only in M and 33 only in the L region (Table 3; Appendix 1).

When species that were unique to a region were excluded from the analysis, as well as species that occurred at fewer than 5 sites (leaving only 65 of the original 139 species), the first 2 axes of the restricted CA still separated the regions in the same way as the full dataset (data not shown). An examination was also undertaken of the next few CA axes, but these revealed no further clear separation of sites and/or species (data not shown), reflecting the magnitude of the corresponding eigenvalues and their slow decline. These results indicate that after accounting for regional differences, there are no dominant gradients accounting for site differences within regions; i.e. there was not dominant effects of tillage, crop rotation, weed management etc.

Relative abundance of species

Due to the regional trends identified in the correspondence analysis, r_{ab} values were calculated on a regional basis using sites at each sampling time as the sampling unit. Within all regions relative abundance was highly skewed with 75% or more of species having values lower than the mean (Fig. 4). Thus a few species contributed most to r_{ab}, as indicated by the 10 species with the highest values in each region (Table 4). When combined into 1 group, these 10 most abundant species within each region gave relative abundance scores of 0.48, 0.53, 0.63 and 0.73 for regions L, M, G and K, respectively (Table 4).

Of the 8 species found in all 4 regions, 6 also featured among the highest r_{ab} values in one or more of the regions. *Avena* spp. and *Sonchus* spp. were in the top 10 highest r_{ab} values in L, M and G regions, *Lamium amplexicaule* in L and K regions, *Raphanus raphanistrum*, *Coronopus didymus* and

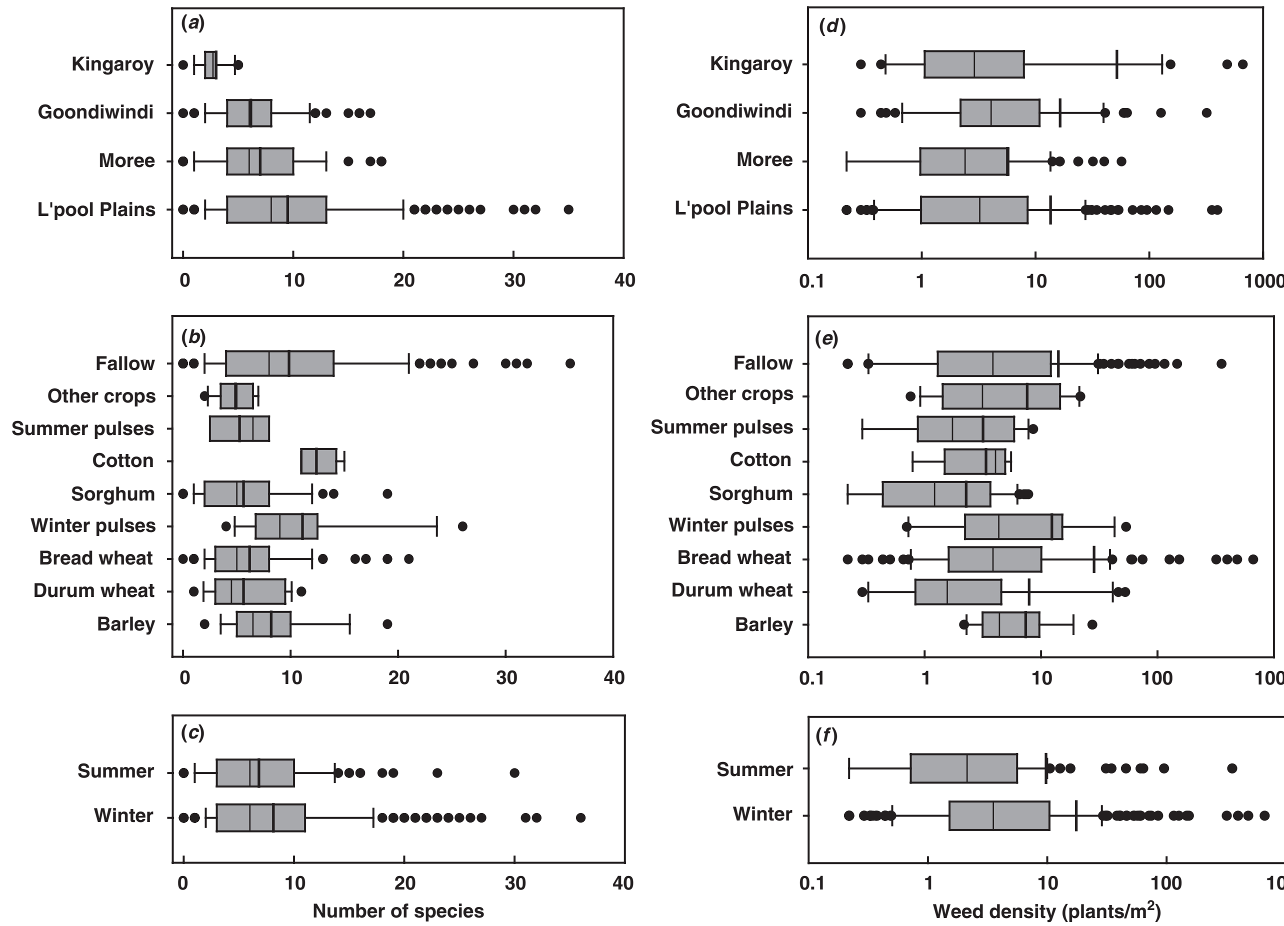

Figure 1. Box plots of species richness across (*a*) regions, (*b*) crops and (*c*) sampling season and species density across (*d*) regions, (*e*) crops and (*f*) sampling season (note log scale for weed density). The line within each box is the median, the heavy solid line is the mean, the box demarcates the 25th and 75th percentiles, error bars indicate 10th and 90th percentiles and dots are 'outliers'. L'pool Plains, Liverpool Plains region.

Amaranthus spp. in the K region, and *Rapistrum rugosum* in the M region (Table 4). Other species with high r_{ab} values in a number of regions included, *Convolulus erubescens* in L, M and K, and *Echinochloa* spp. in L, M and G, *Polygonum* spp. in L and M, and *Phalaris paradoxa* in M and G. Conversely, a few species which were recorded only in one region were also calculated to have high r_{ab} values including, volunteer soybean and *Stachys arvensis* in K, and *Crassula* spp. in L (Table 4), suggesting regional if not local high abundance. Volunteer sorghum and faba bean crop species also had among the 10 highest r_{ab} values in the M region.

The 8 species observed in all regions were also widespread across sites. *Sonchus* spp. were recorded at 94% of sites (Table 5), with r_{ab} values of 0.061, 0.093, 0.172, 0.014 in L, M, G and K, respectively; *Avena* spp. were recorded on 91% of sites with r_{ab} values of 0.069, 0.242, 0.153 and 0.007, for L, M, G and K, respectively (Appendix 1).

In all, 33 species occurred in 3 regions, and of these *Echinochloa* spp. were present at 78% of the sites with r_{ab} values of 0.083, 0.039 and 0.144 and *Phalaris paradoxa* on 76% of sites with r_{ab} values of 0.019, 0.068 and 0.065 for L, M and G, respectively, *C. erubescens* was found at 76% of sites (r_{ab} values of 0.024, 0.043 and 0.041 for L, M and K regions), and wind-dispersed species *Conyza* spp., *Lactuca serriola* and *Euchiton/Gamochaeta* species, occurred on 83, 74 and 70% of sites, respectively (G, L and M) but had low r_{ab} values (Appendix 1). A total of 42 species occurred in 2 regions.

Discussion

The diverse weed flora identified by this study in the NGR exceeded 139 species. Whilst there was no indication of weed species assemblages due to temporal or management influences, there was an indication of spatial influences. Separate assemblages of a small number of species were identified for the Kingaroy and Goondiwindi regions which both differed from the majority of species that occurred in the Moree and Liverpool Plains regions. Despite this high

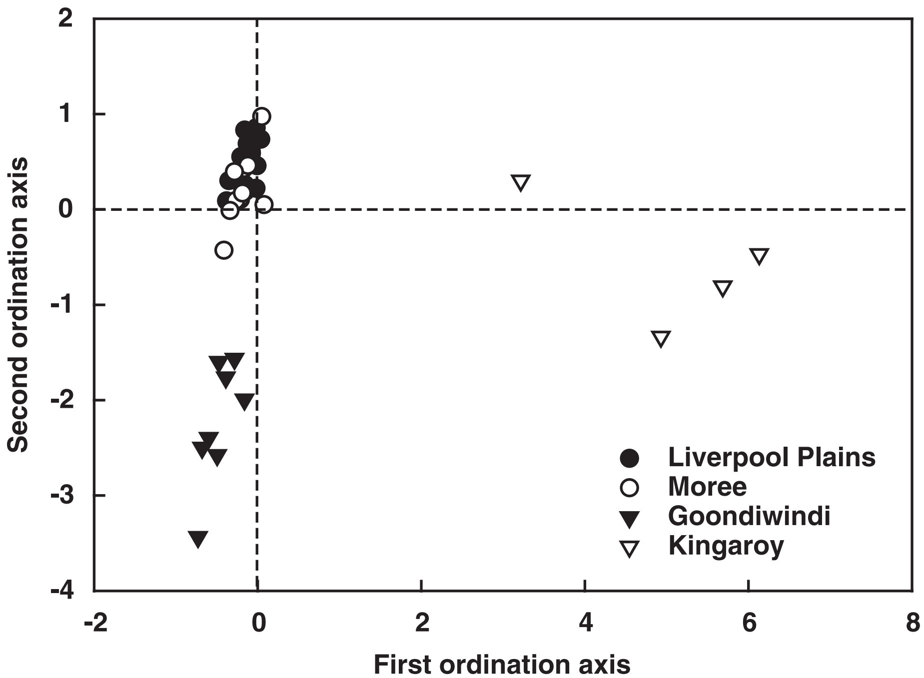

Figure 2. Correspondence analysis showing the first 2 ordination axes using sites as the dependent variable.

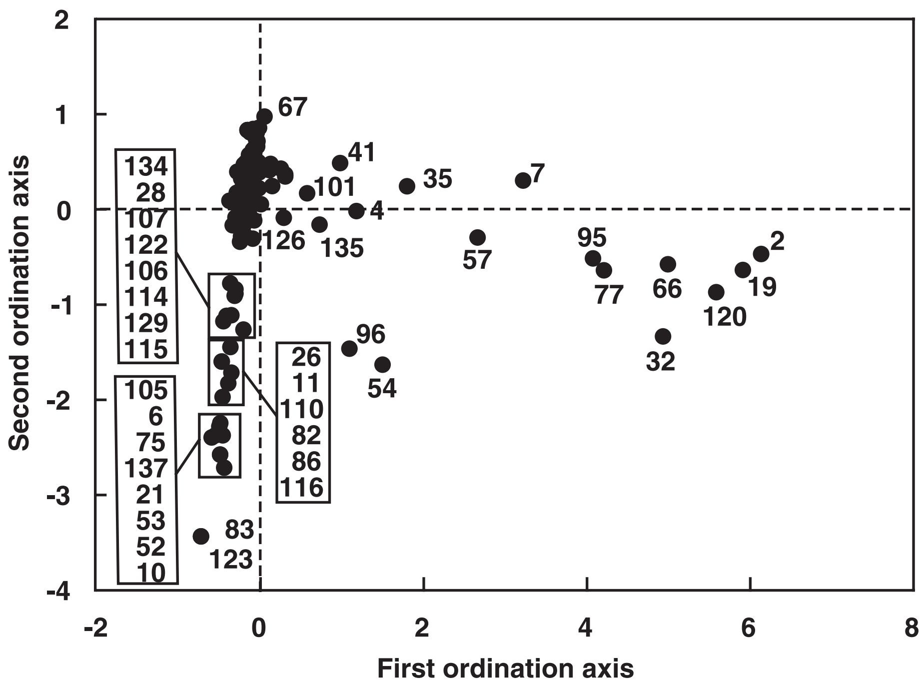

Figure 3. Correspondence analysis showing the first 2 ordination axes using species as the dependent variable. For numbered index of species see Appendix 1. Points without numbers were observed in the Liverpool Plains and Moree regions.

species richness, generally only a few species dominated at any 1 site at any single point in time.

The main species observed, if not their ubiquity, were similar to those reported from a mail and paddock surveys conducted at wheat harvest by Martin *et al*. (1988), paddock surveys conducted in the summer by Felton *et al*. (1994), and mail and field surveys conducted by Alemseged *et al*. (2001). Alemseged *et al*. (2001) reported on grain growers' views of

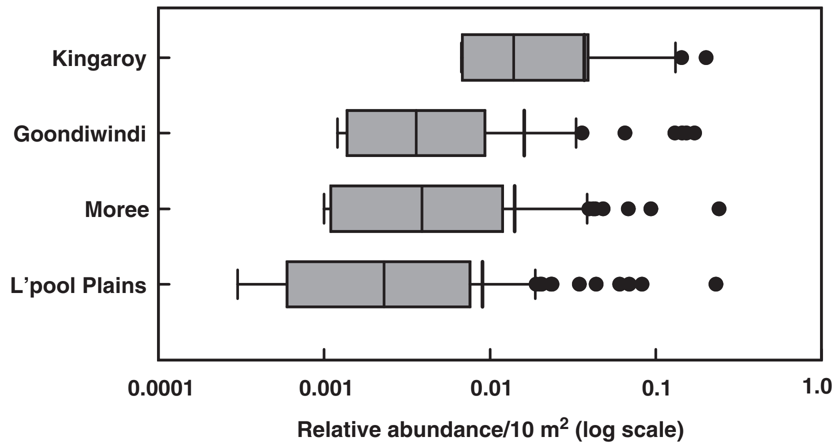

Figure 4. Box plot of species relative abundance within regions (excluding species not recorded in a region, see Appendix 1). The line within each box is the median, the heavy solid line is the mean, the box demarcates the 25th and 75th percentiles, error bars indicate 10th and 90th percentiles and dots are 'outliers'. Note log scale. L'pool Plains, Liverpool Plains region.

Table 4. Relative abundance (r_{ab}) ranking of the top 10 species in each region and their combined value over the whole study period, May 1997–July 2000

Liverpool Plains		Moree		Goondiwindi		Kingaroy	
Species	r_{ab}	Species	r_{ab}	Species	r_{ab}	Species	r_{ab}
Lamium amplexicaule	0.231	*Avena* spp.	0.242	*Sonchus* spp.	0.172	*Coronopus didymus*	0.201
Echinochloa spp.	0.083	*Sonchus* spp.	0.093	*Avena* spp.	0.153	*Raphanus raphanistrum*	0.143
Avena spp.	0.069	*Phalaris paradoxa*	0.068	*Echinochloa* spp.	0.144	*Lamium amplexicaule*	0.129
Sonchus spp.	0.061	*Medicago* spp.	0.048	*Sisymbrium* spp.	0.130	*Stachys arvensis*	0.119
Fallopia convolvulus	0.044	*Convolvulus erubescens*	0.043	*Phalaris paradoxa*	0.065	*Glycine max*	0.060
Crassula spp.	0.035	*Rapistrum rugosum*	0.042	*Cirsium vulgare*	0.036	*Convolvulus erubescens*	0.041
Convolvulus erubescens	0.024	*Echinochloa* spp.	0.039	*Euphorbia* spp.	0.027	*Daucus glochidiatus*	0.039
Lactuca serriola	0.023	*Sorghum bicolor*	0.035	*Euchiton* and *Gamochaeta* spp.	0.024	*Amaranthus* spp.	0.035
Conyza spp.	0.020	*Vicia faba*	0.034	*Solanum nigrum*	0.023	*Ipomoea plebeia*	0.034
Polygonum spp.	0.020	*Polygonum* spp.	0.028	*Tetragonia tetragonoides*	0.019	*Erodium* spp.	0.022
Combined r_{ab}	0.475		0.528		0.623		0.730

the most difficult to control weeds in the NGR which included, *Avena* spp., *Brassica tournefortii*, *P. paradoxa*, *Sonchus* spp., *Polygonum aviculare*, *Lolium rigidum*, *Fallopia convolvulus*, *R. raphanistrum*, *Argemone mexicana* and *Arctotheca calendula*. An earlier mail survey to growers by Martin *et al.* (1988) had resulted in a similar but not identical list of troublesome weeds, *Avena* spp., *R. rugosum*, *P. aviculare*, *P. paradoxa*, *F. convolvulus*, *Silybum marianum*, *Carthamus lanatus*, *Sisymbrium orientale* and *Lolium* spp. Some of the species perceived as the worse problems were reflected in our site ubiquity and relative abundance values for each region, for example *Avena* spp., *P. paradoxa*, *Sonchus* spp., *P. aviculare*, *F. convolulus* and *R. raphanistrum* but others were neither found very frequently nor at high abundance. We observed only *L. rigidum*, *B. tournefortii*, *C. lanatus* and *A. ochroleuca* at the Liverpool Plains sites. *Arctotheca calendula* was not recorded at any sites, although it was only ranked as an important weed by 6% of growers (Alemseged *et al.* 2001). Identification of the different Brassicaceae weeds was found to be poor in a separate survey (L. J. Rew, A. Storrie unpublished data) and is further confused by the use of common names. Because of these anomalies in identification, comparison of the relative importance of these species between the surveys is pointless. In our sampling *R. raphanistrum* and *Sisymbrium* species had similar relative

Table 5. Percentage of sites ($n = 46$) on which particular species occurred during May 1997–July 2000

Only species which occurred on 50% or more sites are listed

Species	Proportion of sites (%)
Sonchus spp.	93.5
Avena spp.	91.3
Conyza spp.	82.6
Echinochloa spp.	78.3
Convolvulus erubescens	76.1
Phalaris paradoxa	76.1
Lactuca serriola	73.9
Euchiton and Gamochaeta spp.	69.6
Cirsium vulgare	69.6
Medicago spp.	67.4
Raphanus raphanistrum	65.2
Hypochaeris radicata	56.5
Lamium amplexicaule	56.5
Rapistrum rugosum	56.5
Silybum marianum	54.4
Sorghum bicolor	54.4
Fallopia convolvulus	52.2
Urochloa panicoides	50.0

abundance overall, *R. rugosum* was lower and *B. tournefortii* the lowest.

Felton *et al*. (1994) surveyed 65 uncultivated fallow and 25 sorghum paddocks during the summer of 1989 and observed 87 and 51 different species, respectively. In their study, *C. erubescens*, *E. crus-galli*, *U. panicoides*, *Panicum decompositum*, *Conyza* spp. and *S. oleraceus* were the most ubiquitous, observed in more than 50% of fallow paddocks; *C. erubescens*, *E. crus-galli*, *U. panicoides*, *P. decompositum*, *Hibiscus trionum*, *Portulaca oleracea*, *P. aviculare*, *Tribulus* spp., *Xanthium spinosum*, *Avena* spp. and *Eragrostis cilianensis* were most ubiquitous (more than 50%) in sorghum paddocks. All of these species were recorded at our sites though only *C. erubescens*, *Echinochloa* spp., *Sonchus* spp., *Conyza* spp., *Avena* spp. and *U. panicoides* were observed at more than 50% of the sites.

About 2 decades ago almost half of farmers in the southern part of the NGR followed a continuous wheat rotation, one third a wheat–sorghum rotation and about one-fifth a wheat–legume rotation (Medd *et al*. 1995 based on Martin *et al*. 1988). The general perception in the mid to late 1990s was that more farmers in the NGR region were aiming for a wheat–sorghum and long fallow rotation, growing 2 crops over 3 years. However, adhering to any rotation is often thwarted by climatic and economic volatility (Martin *et al*. 1988), as found in our study. A change towards more opportunity cropping and/or diverse cropping sequences is apparent given the 7 winter crops and 6 summer crops grown in what ostensibly had been nominated by the participating farmers as sites in a wheat–sorghum rotation. The fact that many farmers appear to be following a more opportunity cropping approach by incorporating information on available soil moisture and market values endorses the work of Hayman *et al*. (1996) and others, the extension service and decision support models such as ‘Wheatman’ (Woodruff 1992) even though adoption of such models been poor (Hayman and Easdown 2002).

All 13 crop species grown on sites involved in the study were observed as volunteer weeds which is characteristic of the subtropical region. Soybean attained the fifth highest relative abundance value in the Kingaroy region, and sorghum and faba bean were eight and ninth highest in the Moree region. Other than Roundup Ready cotton, which was first grown commercially in the region in 2000 after this study was completed, canola is the only other herbicide tolerant crop presently grown commercially in Australia. Only 1 site in 1 year sowed triazine resistant canola. Should herbicide tolerant crops be more widely adopted in the future, the high abundance of many of the crops as volunteers suggests that they would become a major weed issue in the NGR. Glyphosate resistant varieties would be of particular concern since glyphosate is the main chemical used during the fallow period. This supports the views and reservations about such varieties put forwards by Medd *et al*. (1995). Already a biotype of *L. rigidum* resistant to glyphosate has been selected for in the region (Storrie and Cook 2002), signalling the problem of over reliance on this herbicide for fallow management.

There is a perception by farmers and researchers that the increased adoption of conservation tillage practices has led to an associated change in the weed spectrum. ‘Shifts in weed flora are part of the folklore of weed science and indeed have taken place throughout agricultural history’ (Medd 1987). There is no indication in our study of any species shifts having occurred from either the adoption of conservation tillage or opportunity cropping. The correspondence analysis highlighted some regional trends in weed associations but as no further separation of species was readily apparent it can be inferred that particular practices, for example tillage, crop rotation or agrochemical input had no identifiable bearing on the weed flora. Nevertheless, weed assemblages observed in any paddock are purported to result from management practices (tillage, crop rotation, sowing time, row spacing, weed management practices, Buhler 2002). Climate or the introduction of seeds from areas outside the paddock (e.g. as crop seed contamination, on machinery, wind-dispersal) may also influence assemblages. Upon examination, there is nothing especially remarkable about the species assemblages separated by the correspondence analysis. Both the Goondiwindi and Kingaroy groups involved a range of annual and perennials as well as broadleaved and grass species and there appeared to be no functional relationship within the species groups in terms of their seasonality.

Felton *et al*. (1994) found that weed density and species richness was generally lower in fallow paddocks that had been treated with herbicide (glyphosate and/or atrazine) compared with fallows where tillage was practiced. While we found no evidence of cultural influences on the fallow flora, there was an indication of higher species diversity in fallows. Canadian experience has shown that weed spectrum changes cannot be related to tillage practices alone (Derksen *et al*. 1993). Subsequently Leeson *et al*. (2000) found that cropping history had the largest influence on weed communities from a survey of 28 farms and about 300 commercial fields sampled in Saskatchewan; herbicide had the second largest impact on weed species assemblages. Thus, numerous site-specific factors need to be considered before the weed assemblages or changes to assemblages can be fully explained.

Despite the diversity of management practices underlying our study the average number of species observed in a site over the study period was about 6 at any sampling time, varying slightly among regions and crops; and the median number of species observed at any sampling time was between 4 and 8 depending on the crop and sampling period. Most sites had some form of crop rotation that involved both summer and winter crops; farms in the Goondiwindi region were the exception in tending to grow wheat repeatedly. Doucet *et al*. (1999) asserted that crop rotation is generally perceived to reduce weed density and maintain species richness, thus preventing dominance of a few weeds, which is a possible explanation for the high species richness and generally low weed abundance observed in this study. In the NGR rainfall can occur all year around but much falls in summer storms and most rain events result in flushes of weeds. Separating the data into summer or winter crops, to differentiate species which germinate in those seasons, revealed little difference in species richness and that relative abundance values declined quite rapidly between the first, second, third and fourth most abundant species (data not shown). This suggests that a few species are dominating in the different seasons, as well as on a regional basis.

This study demonstrates that a large number of species (at least 139) are present in the NGR, although only 8 species were recorded in all 4 regions. The highest species richness was observed in the Liverpool Plains (111 species) and Moree (71) regions and may be related to their long history with livestock production that may have fostered the spread of weed propagules. Prior to the 1960s these regions were predominately grazing rangelands, at which time it became possible to crop the heavy vertisol soils due mainly to changes in tillage practices (Marcellos and Felton 1992). Interestingly, species richness was considerably lower in the Kingaroy region where continuous rotational cropping is practiced on the highly structured krasnozem type soils. Irrespective of location, the relative abundance values of most species were low, which suggests farmers were effectively managing their weeds. However, a number of different species obtained higher relative abundance values in several regions and sites demonstrating the environmental plasticity and adaptability of such species. With such a broad base to the weed flora it is reasonable to expect that regardless of the environment or cultural/management practices adopted, some species will have potential to benefit and become dominant in different crops and seasons.

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Appendix 1. Relative abundance of species, listed alphabetically by scientific name, recorded in the Liverpool Plains (L), Moree (M), Goondiwindi (G) and Kingaroy (K) regions within the subtropical grain region of Australia

Values are means for the total study period of May 1997 to July 2000
Species nomenclature follows the Flora of New South Wales (Harden 1990, 2002)

Index	Species	Common name	L	M	G	K
1	*Abelmoschus ficulneus*	Native rosella	0.0006	—	—	—
2	*Acanthospermum hispidum*	Starburr	—	—	—	0.0068
3	*Amaranthus macrocarpus*	Dwarf amaranth	0.0048	0.0010	—	0.0068
4	*Amaranthus* spp.	Amaranth	0.0033	0.0010	0.0024	0.0353
5	*Ammi majus*	Bishops weed	0.0073	0.0010	—	—
6	*Anagallis arvensis*	Scarlett pimpernel	—	—	0.0110	—
7	*Anoda cristata*	Anoda weed	—	—	—	0.0136
8	*Argemone ochroleuca*	Mexican poppy	0.0069	—	—	—
9	*Asphodelus fistulosus*	Onion weed	0.0049	—	—	0.0068
10	*Atriplex* spp.	Annual saltbush	—	—	0.0024	—
11	*Avena sativa*	Volunteer oats	—	—	0.0012	—
12	*Avena* spp. (*A. fatua* and *A. ludoviciana)*	Wild oats	0.0693	0.2415	0.1533	0.0071
13	*Bidens pilosa*	Cobbler's pegs	0.0012	—	—	—
14	*Boerhavia dominii*	Tarvine	0.0016	0.0010	—	—
15	*Brassica tournefortii*	Wild turnip	0.0003	—	—	—
16	*Buglossoides arvensis* (= *Lithospermum arvense*)	Corn gromwell	0.0025	—	—	—
17	*Capsella bursa–pastoris*	Shepherd's purse	0.0038	—	—	—
18	*Carthamus lanatus*	Saffron thistle	0.0026	—	—	—
19	*Cenchrus echinatus*	Mossman River grass	—	—	—	0.0148
20	*Centaurea* spp.	Cockspurs	0.0009	—	0.0024	—
21	*Centaurium* spp.	Centuary	—	—	0.0054	—
22	*Centipeda thespidioides*	Desert sneezeweed	—	0.0022	—	—
23	*Cerastium glomeratum*	Mouse-ear chickweed	0.0020	0.0021	—	—
24	*Chenopodium album*	Fathen	0.0014	0.0015	0.0012	—
25	*Chenopodium pumilio*	Clammy goosefoot/crumbweed	0.0012	—	0.0024	—
26	*Chenopodium* spp.	Goosefoot	0.0004	—	0.0035	—
27	*Chloris* spp.	Windmill grass	0.0118	0.0030	—	—
28	*Chondrilla juncea*	Skeleton weed	0.0009	—	—	—
29	*Cicer arientinum*	Volunteer chickpea	0.0006	0.0010	0.0027	—
30	*Cirsium vulgare*	Spear thistle	0.0075	0.0119	0.0359	—
31	*Citrullus colocynthis*	Colocynth	0.0029	0.0039	—	—
32	*Citrullus lanatus*	Paddy melon	0.0046	0.0029	0.0036	—
33	*Commelina benghalensis*	Hairy wandering jew	—	—	—	0.0067
34	*Convolvulus erubescens*	Australian bindweed	0.0237	0.0431	—	0.0407
35	*Conyza* spp.	Fleabanes	0.0205	0.0257	0.0176	—
36	*Coronopus didymus*	Swinecress	0.0009	—	—	0.2011
37	*Cotula australis*	Common cotula	0.0004	—	—	—
38	*Crassula* spp. (inc. *C. sieberiana*)	Crassula	0.0347	—	—	—
39	*Cullen tenax* (= *Psoralea tenax*)	Emu foot	0.0024	0.0050	—	—
40	*Cyclospermum leptophyllum*	Slender celery	0.0020	—	0.0024	—
41	*Cynodon dactylon*	Couch	0.0015	0.0010	—	0.0067
42	*Cyperus* spp.	Sedge	0.0011	0.0091	—	—
43	*Datura* spp.	Thornapple	0.0072	0.0022	—	0.0068
44	*Daucus glochidiatus*	Australian carrot	0.0100	0.0010	—	0.0392
45	*Dichanthium sericeum*	Queensland bluegrass	0.0023	0.0039	0.0036	—
46	*Dichanthium setosum*	Dichanthium	0.0006	—	—	—
47	*Digitaria ciliaris*	Summer grass	0.0032	0.0066	—	—
48	*Echinochloa* spp.	Native millet	0.0026	0.0020	0.0014	—
49	*Echinochloa* spp. (*E. colona*, *E. crus-galli*)	Barnyard grass	0.0827	0.0395	0.1437	—
50	*Echium plantagineum*	Paterson's curse	0.0003	—	—	—
51	*Einadia nutans*	Berry saltbush	0.0003	0.0103	—	—

Appendix 1. Continued

Index	Species	Common name	L	M	G	K
52	*Einadia trigonos* (= *Chenopodium trigonos*)	Fishweed	—	—	0.0012	—
53	*Eleusine indica*	Crowsfoot grass	—	—	0.0012	—
54	*Emex australis*	Spiny emex	—	—	0.0024	0.0213
55	*Epilobium hirtigerum* and *E. billardierianum* subsp. *cinereum*	Hoary willowherb	0.0018	0.0010	—	—
56	*Eriochloa pseudoacrotricha*	Early spring grass	—	0.0011	—	—
57	*Erodium* spp.	Crowsfoot	0.0006	—	—	0.0224
58	*Euchiton* and *Gamochaeta* spp. (inc. *E. sphaericus*, *G. spicata*)	Cudweeds	0.0124	0.0203	0.0237	—
59	*Euphorbia* spp.	Euphorbia	0.0101	0.0099	0.0267	—
60	*Fallopia convolvulus*	Black bindweed	0.0438	0.0160	—	—
61	*Flaveria australasica*	Yellow twin-stem/speedy weed	0.0018	—	0.0050	—
62	*Fumaria densiflora*	Fumitory	0.0012	—	—	—
63	*Galium aparine*	Cleavers	0.0003	—	—	—
64	*Geranium molle*	Dove's foot cranesbill	0.0003	—	—	—
65	*Geranium solanderi*	Australian cranesbill	0.0003	—	—	—
66	*Glycine max*	Volunteer soybean	—	—	—	0.0598
67	*Gossypium hirsutum*	Volunteer cotton	—	0.0025	—	—
68	*Haloragis* spp.	Raspweed	0.0073	0.0010	—	—
69	*Helianthus annuus*	Native sunflower	0.0003	0.0010	—	—
70	*Helianthus annuus*	Volunteer sunflowers	0.0027	—	—	—
71	*Hibiscus trionum*	Bladder ketmia	0.0099	0.0061	—	—
72	*Hordeum* spp.	Barley grass	0.0003	—	—	—
73	*Hordeum vulgare*	Volunteer barley	0.0003	—	—	—
74	*Hypochaeris glabra*	Smooth catsear/flatweed	—	—	0.0099	—
75	*Hypochaeris radicata*	Flatweed/common catsear	0.0142	0.0052	0.0013	—
76	*Ibicella*, *Martynia* and *Proboscidea* spp.	Devil's claw	0.0003	—	—	—
77	*Ipomoea lonchophylla*	Cowvine	0.0013	0.0049	—	—
78	*Ipomoea plebeia*	Bellvine	—	0.0010	—	0.0345
79	*Iseilema membranaceum*	Small flinders grass	—	0.0020	—	—
80	*Lactuca saligna*	Willow lettuce	0.0006	—	—	—
81	*Lactuca serriola*	Prickly lettuce	0.0233	0.0238	0.0012	—
82	*Lamium amplexicaule*	Deadnettle	0.2306	0.0010	0.0012	0.1288
83	*Lepidium* spp. (mainly *bonariense*)	Peppercress	0.0003	0.0020	0.0071	—
84	*Leptochloa divaricatissima*	Cane grass	—	—	0.0012	—
85	*Lolium* spp.	Ryegrass	0.0123	—	—	—
86	*Malva parviflora*	Small flowered mallow/marshmallow	0.0087	0.0045	0.0071	—
87	*Malvastrum* spp.	Malvastrum	0.0008	—	0.0048	—
88	*Marrubium vulgare*	Horehound	0.0009	—	—	—
89	*Medicago* spp. (*M. minima*, *M. polymorpha*)	Medics	0.0181	0.0482	0.0118	—
90	*Onopordum acanthium*	Scotch thistle	0.0003	—	—	—
91	*Oxalis* spp.	Oxalis	0.0023	0.0080	0.0036	—
92	*Panicum* spp.	Panics	0.0054	0.0065	—	—
93	*Papaver* spp.	Poppy	0.0009	—	—	—
94	*Phalaris paradoxa*	Paradoxa grass	0.0190	0.0684	0.0651	—
95	*Phaseolus vulgaris*	Volunteer navy bean	—	—	—	0.0136
96	*Physalis* spp.	Ground cherries	—	0.0010	0.0037	0.0067
97	*Picris hieracioides*	Hawkweed	0.0003	—	—	—
98	*Poa annua*	Winter grass	0.0019	—	—	—
99	*Polygonum* spp. (*P. aviculare*, *P. patulum*)	Wireweed, tree hogweed	0.0200	0.0283	0.0050	—
100	*Portulaca oleracea*	Pigweed	0.0058	0.0029	0.0024	—
101	*Raphanus raphanistrum*	Wild radish	0.0071	0.0124	0.0024	0.1432

Appendix 1. Continued

Index	Species	Common name	L	M	G	K
102	*Rapistrum rugosum*	Turnip weed	0.0100	0.0420	0.0048	0.0067
103	*Rhynchosia minima*	Ryncho	0.0035	0.0117	—	—
104	*Ricinus communis*	Castor oil	0.0006	—	—	—
105	*Rubus* spp.	Blackberry	—	—	0.0038	—
106	*Rumex* spp.	Docks	0.0003	—	0.0012	—
107	*Salsola kali*	Soft roly poly	0.0023	—	0.0049	—
108	*Salvia reflexa*	Mintweed	0.0090	0.0010	0.0024	—
109	*Scleroblitum atriplicinum*	Purple goosefoot	0.0054	0.0054	—	—
110	*Sclerolaena birchii*	Galvanised burr	—	—	0.0012	—
111	*Sesbania cannabina*	Sesbania pea	0.0003	—	—	—
112	*Sida cordifolia*	Flannel weed	0.0023	0.0019	—	—
113	*Silybum marianum*	Variegated thistle	0.0137	0.0163	—	—
114	*Sisymbrium* spp. (*S. officinale*, *S. orientale*, *S. thellungii*)	Mustards	0.0089	0.0039	0.1301	—
115	*Solanum americanum*	Glossy nightshade	—	0.0010	0.0012	—
116	*Solanum nigrum*	Blackberry nightshade	0.0003	—	0.0230	—
117	*Soliva anthemifolia*	Dwarf jo-jo	0.0006	0.0032	—	—
118	*Sonchus* spp. (*Sonchus asper*, *S. oleraceus*)	Sowthistles	0.0605	0.0933	0.1716	0.0135
119	*Sorghum bicolor*	Volunteer sorghum	0.0155	0.0345	0.0124	—
120	*Stachys arvensis*	Stagger weed	—	—	—	0.1187
121	*Taraxacum officinale*	Dandelion	0.0003	0.0019	—	—
122	*Tetragonia tetragonioides*	New Zealand spinach	0.0015	—	0.0186	—
123	*Trianthema portulacastrum*	Giant pigweed	—	—	0.0012	—
124	*Tribulus terrestris*	Caltrop	0.0076	0.0088	0.0012	—
125	*Trifolium* spp.	Clover	0.0006	—	—	—
126	*Triticum aestivum*	Volunteer wheat	0.0069	0.0042	0.0067	0.0162
127	*Urochloa panicoides*	Liverseed grass	0.0145	0.0098	0.0080	0.0139
128	*Urtica* spp.	Stinging nettle	0.0086	—	0.0026	—
129	*Verbena* spp.	Verbena	—	0.0039	0.0048	—
130	*Veronica* spp. (inc. *V. peregrina*)	Speedwell	0.0021	—	—	—
131	*Vicia faba*	Volunteer faba bean	0.0006	0.0344	—	—
132	*Vignia radiata*	Volunteer mungbeans	0.0011	—	—	—
133	*Vittadinia sulcata*	Fuzzweed	0.0068	0.0019	—	—
134	*Wahlenbergia* spp.	Bluebells	0.0015	0.0010	0.0091	—
135	*Xanthium occidentale*	Noogoora burr	0.0030	—	0.0026	0.0086
136	*Xanthium spinosum*	Bathurst burr	0.0015	0.0010	0.0012	—
137	*Xerochrysum bracteatum* (= *Bracteantha bracteata*)	Golden everlasting	—	—	0.0012	—
138	*Zea mays*	Volunteer maize	0.0007	—	—	—
139	Unknown	Unknown	0.0025	0.0168	0.0024	—