Comparative survey of weeds surviving in triazine-tolerant and conventional canola crops in south-eastern Australia

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Abstract
Many farmers grow triazine-tolerant (TT) canola to enable control of difficult weeds and to allow early sowing. The efficacy of triazine herbicides in canola influences the development of future weed problems. A survey was conducted to determine the incidence and abundance of weeds surviving in TT and conventional canola crops across south-eastern Australia. Fifty-five canola paddocks (27% TT and 73% conventional) were selected at random in August/September 1998 when most weed management practices were already completed by farmers. Seventy-three weed species were identified, some at densities of up to several hundred plants m^{-2}. This has serious implications for weed seedbank replenishment and the perpetuation of weed populations requiring control in future crops. The most widespread grass species at more than 30% of sites were *Lolium rigidum*, *Avena* spp., and *Vulpia* spp., while the main broadleaf weeds were *Arctotheca calendula, Polygonum aviculare,* and *Fumaria* spp. Some weeds were more prevalent in conventional canola (e.g. *Fumaria* spp., *Arctotheca calendula, Capsella bursa-pastoris* and *Papaver somniferum*) while others were more common in TT (e.g. *Anagallis arvensis, Raphanus raphanistrum, Lepidium africanum* and *Conringia orientalis*). These results suggest that widespread adoption of TT canola will affect weed population dynamics in canola thereby leading to new weed problems in canola.

Introduction
Canola, an expanding crop in the southern wheat-belt of Australia, enables more diverse and profitable cropping rotations. The recent availability of triazine-tolerant (TT) cultivars provides opportunities for growers to sow early and use triazine herbicides (pre-and post-emergence) for control of difficult weeds like *Raphanus raphanistrum* (wild radish), *Fumaria* spp. (fumitory), *Capsella bursa-pastoris* (shepherd's purse), as well as *Lolium rigidum* (annual ryegrass) which has widespread resistance to other herbicide mode-of-action groups. TT canola also gives flexibility for sowing direct-drilled crops because triazine herbicides do not require incorporation. There has been rapid adoption of TT canola especially in areas infested with *Raphanus raphanistrum* even though yield and oil quality penalties can be associated with TT canola.

Herbicide resistance in weeds is a major problem because it results in reduced grain yields, limited cropping options, and weed management becomes more expensive and complicated requiring greater management skills and long-term planning (Powles *et al.* 1997). At least 22 weed species in the southern cropping region of mainland Australia are now resistant to herbicides from seven different modes of action (Preston *et al.* 1999). The most widespread resistance is to Groups A and B herbicides, although resistance is increasing in incidence to Group C chemicals in *Lolium rigidum* and *Raphanus raphanistrum* (Preston *et al.* 1999). As triazines are widely used in pulse crops and for 'winter cleaning' pastures prior to the cropping phase (Gill and Holmes 1997), an increase in the use of these chemicals in TT canola will further increase the selection pressure for resistance.

The area of production of TT canola is expected to continue to rise because of the benefits outlined above, despite the associated penalties of lower grain yield and oil content, lower resistance to blackleg in some cultivars, greater selection pressure for triazine resistance in weeds, and the persistence of triazine herbicides in alkaline soils. The efficacy of triazine herbicides in canola will influence the development of future weed problems in canola including those with herbicide resistance. The survey reported here was conducted to determine the incidence and abundance of weed species surviving in canola crops after weed control was completed by farmers. Of particular interest was the comparison of weed frequency in TT canola compared with conventional (C) canola.

Materials and methods
The survey was undertaken in August/September 1998. Fifty-five canola crops were selected at random in the south-eastern wheat-belt extending from Young in New South Wales (NSW), through Victoria (Vic), to Tailem Bend in South Australia (SA). The canola growth stage and cultivar, and the soil type and annual average rainfall were recorded at each site. Canola maturity at the time of assessment ranged from the six-leaf stage to flowering. Soils included red-brown earths, and various coloured clays, while the annual average rainfall ranged from 450 to 600 mm. Table 1 shows the distribution of sites across states and crop type. At each site, weed species and plant density were recorded in twenty 1 m^2 quadrats which were spaced at 50 m intervals along a W-transect of the field. The abundance for each species for each site was calculated using the mean of the 20 sample points.

For each weed species a test of equality of incidence between TT and C crops was carried out using Fisher's exact test (see Bishop *et al.* 1975, for example).

The two-way (site by species) table of abundance was explored using the Additive Main effects and Multiplicative Interaction (AMMI) model (Gauch 1992). This involves a singular value decomposition (SVD) of the residuals from an ANOVA of the data under study. The ANOVA includes terms for site and species main effects so the residuals reflect site by species interactions. Due to skewness the abundance data were transformed prior to the ANOVA using $y = \log(a+1)$ where a = abundance (plants m^{-2}). The aim of the AMMI analysis was to summarise site by species interactions in terms of a small number of multiplicative terms (components from the SVD). Each term is the

Table 1. Number of sites sampled in the survey and the codes used to describe these in Figures 2 and 3.

Crop type	New South Wales	South Australia	Victoria	Total
Conventional	23 A	8 B	9 D	40
Triazine-tolerant	9 a	1 b	5 d	15
Total	32	9	14	55

product of site 'loadings' and species 'scores'. These can be viewed graphically using bi-plots (Gauch 1992) in order to explore relationships between sites, between species and between sites and species. Interpretation of the components was sought using additional site information, namely the state, crop type, soil type and rainfall classification. For this purpose one-way ANOVAs for the four explanatory variables were carried out for each set of site loadings.

Results

A total of 73 species was found in the 55 canola paddocks. Twenty-three species were present in at least 10% of the sites (see Table 2). The incidence and abundance (where present) for these species are shown in Figure 1. The most prevalent weed species was *Lolium rigidum* which was found in 86% of the crops. At those sites where present it was found in relatively large numbers with a median density of 4.2 plants m^{-2} but over 300 plants m^{-2} at one site. *Arctotheca calendula* (capeweed) was also very prevalent (67%) but was less abundant (median density of 1.7 plants m^{-2}). Other abundant species present at more than 30% of the sites and at median densities greater than 1 plant m^{-2} were *Polygonum aviculare* (wireweed), *Avena* spp. (wild oats), *Fumaria* spp. and *Vulpia* spp. (silvergrass). *Juncus bufonius* (toad rush) was only present in 16% of the sites but where found was very abundant. *Sisymbrium orientale* (Indian hedge mustard) was at 24% of sites (median density of 1.7 plants m^{-2}) and *Raphanus raphanistrum* was at 13% with a median density of 1.1 plants m^{-2}. Volunteer wheat and barley occurred in 30 and 20% of the crops, respectively.

Weed incidence in TT canola was compared with that in C canola for the 23 most prevalent species (Table 2). The percentage of C canola with *Fumaria* spp. (58%) was significantly (P=0.017) greater than that of TT canola (20%) with this weed. *Arctotheca calendula*, *Capsella bursa-pastoris* and *Papaver somniferum* (opium poppy) were also in a significantly (P<0.1) greater proportion of C crops compared with TT canola. *Anagallis arvensis* (scarlet pimpernel) occurred less frequently (5%) in C canola than in TT canola (27%). *Raphanus raphanistrum* and *Lepidium africanum* (common peppercress) tended to occur more in the TT than in conventional canola, whereas *Polygonum aviculare, Erodium* spp. (storksbill), *Avena* spp. (wild oats) and *Romulea rosea* (onion grass) tended to be less prevalent in TT than in conventional canola. *Conringia orientalis* (hare's ear) was at 3.6% of sites, in a significantly (P =0.07) greater proportion of TT (13 %) than in conventional canola (0%).

In the AMMI analysis of y = log(a+1) where a = abundance (plants m^{-2}) the first three components from the SVD accounted for 23.0, 16.6 and 14.5% of the site by species interaction, respectively. These components therefore accounted for a total of 54.1% of the interaction. Whilst this indicates substantial remaining variation, the first three components may be used to explore relationships. Bi-plots of the scores and loadings for the first component plotted against the second and third components are given in Figures 2 and 3. Species scores are labelled by species number (as given in Table 2) enclosed in a square. They are drawn as lines from the origin. Site loadings are numbered within state and crop type combination (see Table 1) and are prefixed with a code for the combination.

These labels were chosen because there was some evidence that the site loadings for the second component were related to state (P=0.01) and loadings for the third were related to state (P=0.01) and crop type (P=0.02). The components did not relate to soil type or rainfall.

The key characteristic of the bi-plots is that points which are distant from the origin represent sites or species which have large interaction. In terms of species, a large interaction means that the relative abundance of the species changes across sites. Abundance of the species is above/below average at sites which have large loadings in the same/opposite direction from the origin as the species. For example, Figure 2 shows that the abundance of *Lolium rigidum* (species 1) is above average at sites a9, A20 and A19 and below average at sites A15, B6 and a5. The converse is true for *Fumaria* spp. (species 5) and *Capsella bursa-pastoris* (species 9). The abundance of *Polygonum aviculare* (species 3) and *Vulpia* (species 6) is above average at sites A1, A8, a7 and a5. Figure 3 shows that the abundance of *Juncus bufonius* (species 13) is above average at sites A2, A16 and A20 and below average at sites a7 and D8.

Table 2. Incidence of weeds in canola crops in south-eastern Australia. P-value given for the test of equal percentages for conventional (C) and triazine-tolerant (TT) canola crops.

Botanical name	Common name	% C crops with weed	% TT crops with weed	P-value	Total % crops with weed
1. *Lolium rigidum*	Annual ryegrass	83	93	0.423	86
2. *Arctotheca calendula*	Capeweed	75	47	0.059	67
3. *Polygonum aviculare*	Wireweed	65	47	0.235	60
4. *Avena* spp.	Wild oats	60	33	0.129	53
5. *Fumaria* spp.	Fumitory	58	20	0.017	47
6. *Vulpia* spp.	Silvergrass	35	33	1.000	35
7. *Triticum aestivum*	Wheat	33	20	0.510	29
8. *Sonchus oleraceus*	Common sowthistle	25	33	0.735	27
9. *Capsella bursa-pastoris*	Shepherd's purse	30	7	0.086	24
10. *Sisymbrium orientale*	Indian hedge mustard	25	20	1.000	24
11. *Hordeum vulgare*	Barley	18	27	0.468	20
12. *Erodium* spp.	Storksbill	23	7	0.255	18
13. *Juncus bufonius*	Toad rush	20	7	0.417	16
14. *Papaver somniferum*	Opium poppy	20	0	0.091	15
15. *Raphanus raphanistrum*	Wild radish	10	20	0.376	13
16. *Vicia* spp.	Vetch	13	13	1.000	13
17. *Cirsium vulgare*	Spear thistle	13	13	1.000	13
18. *Lactuca serriola*	Prickly lettuce	15	7	0.660	13
19. *Chondrilla juncea*	Skeleton weed	13	7	1.000	11
20. *Anagallis arvensis*	Scarlet pimpernel	5	27	0.041	11
21. *Romulea rosea*	Onion grass	15	0	0.173	11
22. *Malva parviflora*	Small-flowered mallow	13	7	1.000	11
23. *Lepidium africanum*	Common peppercress	8	20	0.329	11

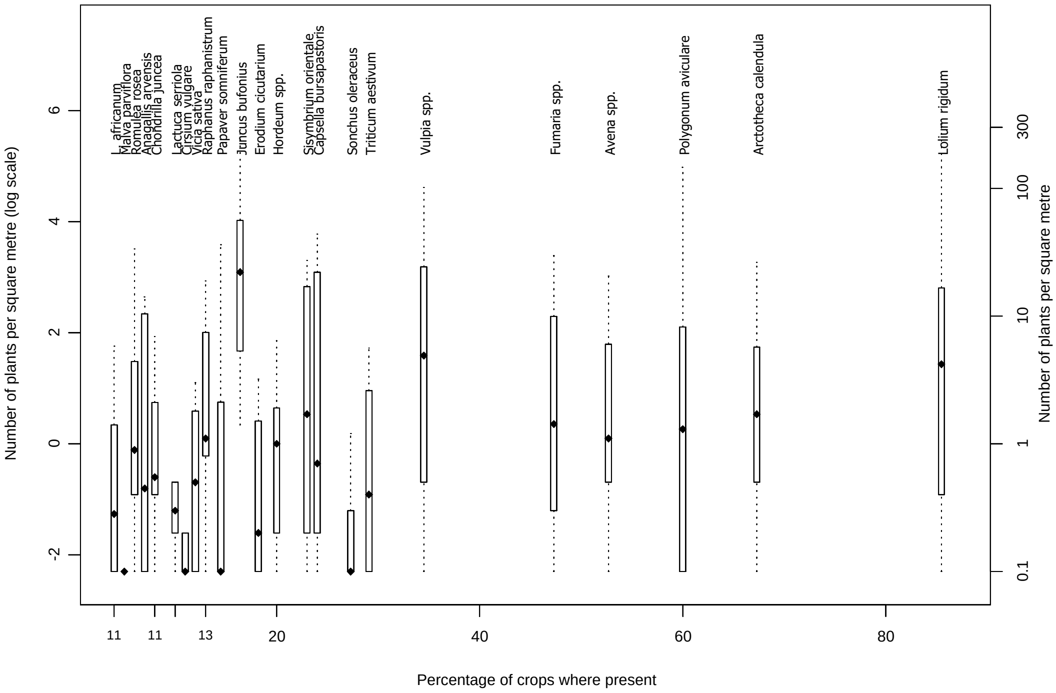

Figure 1. Incidence and abundance of residual weed species in canola crops in south-eastern Australia: x-axis corresponds to the percentage of surveyed crops in which species was found; y-axis shows distribution of log abundance in those crops where species was found (box shows limits of the middle half of the distribution; the solid point within box marks the median value and dotted lines represent lower and upper 25% of the data).

The bi-plots also show relationships and clustering among species. For example, *Fumaria* spp. and *Capsella bursa-pastoris* (species 5 and 9) occur together and do not usually occur with *Lolium rigidum* (species 1). *Polygonum aviculare* and *Vulpia* (species 3 and 6) occur together. Note that a one-way ANOVA of species scores for the first component using an explanatory variable which classifies weed species into grass or broadleaf was significant (P=0.04). The grass types generally have higher scores for the first component (so cluster on the right hand sides of Figures 2 and 3) compared to the broadleaf species. Relationships and clustering of sites were also found. As noted previously, there is some clustering on the basis of state and crop type. The clusters for Vic and SA were similar for TT and conventional canola. *Sisybrium orientale* (species 10) was associated with TT canola in Vic, while *Lolium rigidum, Arctotheca calendula, Polygonum aviculare* and *Vulpia,* (species 1, 2, 3 and 6) were associated with TT crops in NSW (Figure 2). *Fumaria* spp., *Capsella bursa-pastoris* and *Juncus bufonius* (species 5, 9 and 13) were less abundant in TT canola (Figure 3).

Discussion

A surprisingly large number of weeds were found in the survey given that it was conducted after farmers had completed their weed control for the season. There is a perception that TT-canola will provide a 'magic bullet' weed control solution for growers. However, this survey shows that

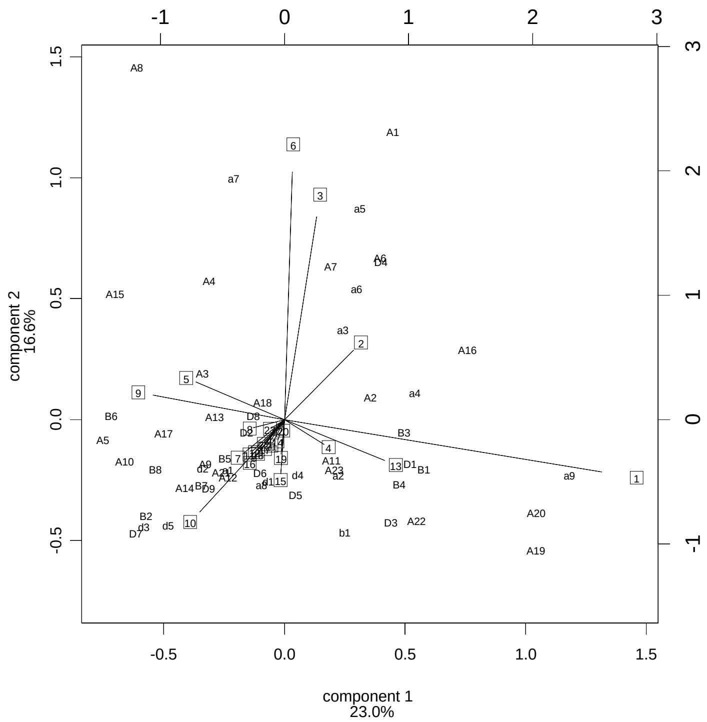

Figure 2. Bi-plot of site loadings (points numbered and labelled with A,a = NSW conventional canola, TT; B,b = SA conventional, TT; D,d = Vic conventional, TT) and species scores (vectors labelled with numbers enclosed in squares, numbers are: 1 = *Lolium rigidum*, 2 = *Arctotheca calendula*, 3 = *Polygonum aviculare*, 4 = *Avena* spp., 5 = *Fumaria* spp. 6 = *Vulpia* spp., 7 = *Triticum aestivum*, 8 = *Sonchus oleraceus*, 9 = *Capsella bursa-pastoris*, 10 = *Sisymbrium orientale*, 11 = *Hordeum vulgare*, 12 = *Erodium* spp., 13 = *Juncus bufonius*, 14 = *Papaver somniferum*, 15 = *Raphanus raphanistrum*, 16 = *Vicia* spp., 17 = *Cirsium vulgare*, 18 = *Lactuca serriola*, 19 = *Chondrilla juncea*, 20 = *Anagallis arvensis*, 21 = *Romulea rosea*, 22 = *Malva parviflora*, 23 =. *Lepidium africanum*) for components 1 and 2 from AMMI analysis of log abundance data.

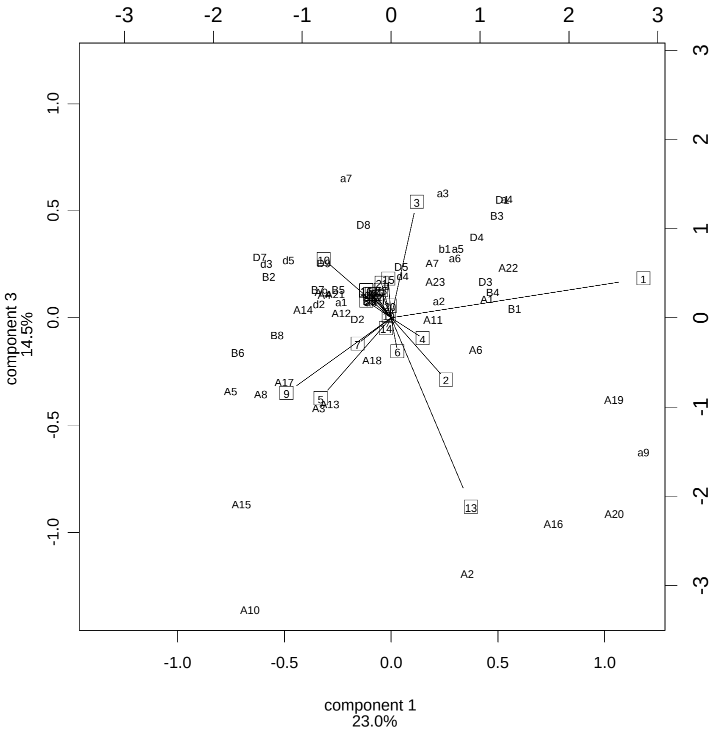

Figure 3. Bi-plot of site loadings (points numbered and labelled with A,a = NSW conventional canola, TT; B,b = SA conventional, TT; D,d = Vic conventional, TT) and species scores (vectors labelled with numbers enclosed in squares, numbers are: 1 = *Lolium rigidum*, 2 = *Arctotheca calendula*, 3 = *Polygonum aviculare*, 4 = *Avena* spp., 5 = *Fumaria* spp. 6 = *Vulpia* spp., 7 = *Triticum aestivum*, 8 = *Sonchus oleraceus*, 9 = *Capsella bursa-pastoris*, 10 = *Sisymbrium orientale*, 11 = *Hordeum vulgare*, 12 = *Erodium* spp., 13 = *Juncus bufonius*, 14 = *Papaver somniferum*, 15 = *Raphanus raphanistrum*, 16 = *Vicia* spp., 17 = *Cirsium vulgare*, 18 = *Lactuca serriola*, 19 = *Chondrilla juncea*, 20 = *Anagallis arvensis*, 21 = *Romulea rosea*, 22 = *Malva parviflora*, 23 = *Lepidium africanum*) for components 1 and 2 from AMMI analysis of log abundance data.

weeds survive even the TT canola weed control practices in sufficient numbers to replenish the seedbank in the soil, and exacerbate subsequent weed infestations. The survival of such large densities of weeds will facilitate the development of herbicide resistance in these weed species. This is of particular concern given the recent appearance of *Raphanus raphanistrum* resistance to triazine herbicides (Preston *et al.* 1999). Therefore, the advantages of herbicide-resistant crops such as TT canola for managing difficult weeds (Powles *et al.* 1997) must be carefully weighed against the risk of increased selection pressure for weed resistance in areas where triazine herbicides have already been used intensively.

The incidence of the most common weeds found in canola in this survey is similar to previous surveys of cereals in south-eastern Australia (Velthius and Amor 1983, Lemerle *et al.* 1996). However, in our survey some broadleaf species were more widespread (for example, *Polygonum aviculare, Fumaria* spp., *Sonchus oleraceus, Capsella bursa-pastoris, Sisymbrium orientale, Erodium* spp., *Papaver* spp. and *Raphanus raphanistrum*). This could be due to changes in species distribution over time, or because these species are harder to control in canola than in cereals. Fewer selective herbicide options are available for broadleaf weeds in canola than in cereals.

The results confirmed that TT canola production reduced the incidence of some weed species as expected. The greater incidence of some species in the TT compared with conventional canola (for example *Anagallis arvensis, Raphanus raphanistrum, Lepidium africanum* and *Conringia orientalis*) indicates that these may become more serious problems as the adoption of TT increases in the future.

The associations between levels of infestation or abundance of certain weed species with crop type and state help to determine patterns affecting weed abundance. Such findings are useful for identifying current or emerging regional problems (for example, *Sisybrium orientale* and *Lepiduim africanum* in TT crops in Victoria). The identification of associations between species (for example *Fumaria* spp. and *Capsella bursa-pastoris*) and species and state (for example *Lolium rigidum, Arctotheca calendula, Polygonum aviculare* and *Vulpia* spp. in TT crops in NSW) will facilitate the development of regional weed management strategies.

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