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Crop responses to sulfonylurea residues in soils of the subtropical grain region of Australia

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Abstract. Crop response following applications of sulfonylurea herbicides can vary considerably across the grain region of subtropical Australia. The aim of the study was to develop recommendations for safe re-cropping following chlorsulfuron, triasulfuron, and metsulfuron-methyl specific for the different soils and climates of this region. Seedling dry matter (SDM) and grain yield were measured at 17 sites over 4 seasons. Soils were ferrosols (pH 5.5–6.8), sodosols (pH 6.6–7.1), and vertosols (pH 7.8–9.0). Sorghum and sunflower were sown at plant-backs between 2 and 20 months, and chickpea at 10–13 months, after applications of sulfonylurea herbicides. Seedling response of the summer crops to these herbicides was substantially different for the 3 soils. Crop response in the ferrosols was largely unaffected by plant-back, soil, or climatic factors after a minimum of 2–3 months. In contrast, response of summer crops in the vertosols and sodosols was strongly affected by plant-backs for up to 10 months, and SDM was more affected in sodosols than in vertosols. Predictive relationships between SDM and plant-back, cumulative temperature, and measured chlorsulfuron residues were developed for sowing summer crops in these soils. In ferrosols and vertosols, chickpea was unaffected by any treatment following plant-back of 10–12 months. These findings indicate that shorter re-cropping is possible in this region than currently recommended. However, the decision should be based not only on plant-back, but on soil type, cumulative temperature, and possibly even residue level in soil. These more specific recommendations will improve the safety and flexibility of re-cropping following applications of sulfonylurea herbicides in this region.

Additional keywords: sorghum, sunflower, chickpea, chlorsulfuron, metsulfuron-methyl, triasulfuron.

Introduction

The sulfonylurea herbicides, chlorsulfuron, triasulfuron, and metsulfuron-methyl, are used extensively for weed control in wheat-growing regions of Australia. Their control of a broad spectrum of weeds, combined with their low application rates and low mammalian toxicity, have contributed to their wide use (Sarmah *et al.* 1998).

However, crop phytotoxicity following applications of sulfonylurea herbicides can vary among different cropping soils and climatic regions across Australia. Currently, there are concerns that the persistence of sulfonylurea residues in the highly alkaline soils of the cooler Mediterranean environment of south-eastern Australia may be affecting growth of sensitive crops and pastures (Wilhelm and Hollaway 1998; Black *et al*. 1999). In contrast, Osten and Walker (1998) found that crops, such as sorghum, sunflower, and chickpea, can be safely sown with short plant-backs in the mildly alkaline soils in the warmer subtropical environment of the Central Highlands of Queensland. These variations in crop phytotoxicity may be due to differences in herbicide degradation rates, which have been shown to increase with soil acidity (Walker *et al*. 1989, 1997), temperature (Walker and Brown 1983; Beyer *et al*. 1987), and, to a lesser extent, soil water content (Oppong and Sagar 1992). As well, soil properties can influence the availability of the residues for plant uptake. Walker *et al*. (1994, 1997) have shown that chlorsulfuron residues were more available in the lighter textured vertosols (grey clays) than in the heavier textured vertosols (black earths), resulting in better weed control. The current re-cropping intervals for selecting crops after sulfonylurea applications have been qualified by soil pH and rainfall through field experiments across the wheat regions

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Table 1. Details of sites with vertosol soils, dates of spraying of chlorsulfuron (C), metsulfuron-methyl (M), triasulfuron (T), plant-backs for sowing of sorghum (Sg), sunflower (Sf), or chickpea (Cp), and cumulative temperature and rainfall between spraying and sowing
Chlorsulfuron residues were determined by bioassay for either 0–10 cm or 0–5 and 5–15 cm depths at sowing, with the italic values for 0–10 cm being calculated from the 0–5 and 5–15 cm measurements

Site	Soil pH (1:5 water)	Clay content (%)	Dates of spraying	Plant-back (months)	Cumulative temperature (max. °C)	Rainfall (mm)	Chlorsulfuron residue (ng/g)			Herbicide (crop)
							0–10 cm	0–5 cm	5–15 cm	
Toowoomba	8.6	71	28.vi.94	6.4[A]	4740	137	*2.8*	4.6	0.5	C (Sg, Sf)
				11.0[A]	8395	380	*0.9*	1.2	0.3	C (Cp)
				19.3[A]	14 410	1188		n.d.	n.d.	C (Sg, Sf)
			26.vi.95	2.7[A]	1670	69	*4.5*	7.5	0.7	C (Sg, Sf)
				7.4[A]	5520	766	*2.5*	3.4	0.8	C (Sg, Sf)
				11.6[A]	8695	1131	*0.8*	0.9	0.3	C (Cp)
				18.3[A]	13 645	1435		—	—	C (Sg, Sf)
Pittsworth	8.8	61	3.vii.95	4.2	2880	133	4.4			C, M, T (Sg)
Warwick	8.7	60	1.viii.95	1.6[A]	1080	13	*6.1*	11.3	0.3	C (Sg, Sf)
				6.2[A]	4980	616	*1.0*	1.0	0.5	C (Sg, Sf)
				10.4[A]	8070	896	*0.7*	0.6	0.4	C (Cp)
				17.2[A]	12 760	1412	*0.3*	0.3	n.d.	C (Sg, Sf)
Gatton	8.4	57	18.vi.96	4.4[A]	3100	149	4.6			C, M, T (Sg)
				6.9	5440	293	1.8			C, M, T (Sg)
				11.8	9600	543	0.4			C, M, T (Cp)
			23.vi.97	4.0[A]	2885	144	2.1			C, M, T (Sg)
				6.6	5400	380	0.4			C, M, T (Sg)
Dalby (1)	7.8	63	22.vi.94	3.0[A]	1870	22	*2.7*	4.5	0.4	C (Sg, Sf)
				4.5	3180	301	3.8			C, M, T (Sg, Sf)
				6.7[A]	5360	162	*0.6*	0.8	0.2	C (Sg, Sf)
				11.7[A]	9460	574	*0.4*	0.5	0.1	C, M, T (Cp)
				19.5[A]	15 650	1182	*0.5*	0.3	0.4	C (Sg, Sf)
			25.vi.95	5.3	3440	303	4.3			C, M, T (Sg)
				12.5	9400	899	*0.4*	0.5	0.1	C, M, T (Cp)
			19.vi.97	4.3[A]	3020	142	—			C, M, T (Sg)
				7.4	6000	384	—			C, M, T (Sg)
Dalby (2)	8.0	47	1.vii.96	3.9[A]	2720	207	1.5			C, M, T (Sg)
				11.2	9300	597	0.1			C, M, T (Cp)
Jondaryan (1)	9.0	72	11.vii.94	6.0[A]	5450	99	*2.6*	3.6	0.8	C (Sg, Sf)
				10.6[A]	9360	222	*1.7*	1.1	0.9	C (Cp)
				18.9[A]	15 900	876	*0.7*	0.6	0.4	C (Sg, Sf)
Jondaryan (2)	7.9	58	6.vi.96	4.7[A]	2790	149	1.1			C, M, T (Sg)
				6.3	4625	224	0.6			C, M, T (Sg)
				12.0	9590	490	n.d.			C, M, T (Cp)
Condamine (1)	8.1	39	1.vii.94	2.6[A]	1810	5	*3.8*	6.1	0.6	C (Sg, Sf)
				6.3[A]	5280	203	*0.2*	0.2	n.d.	C (Sg, Sf)
				11.0[A]	9360	274	*0.1*	0.1	n.d.	C (Cp)
				19.4[A]	16 290	951	*0.1*	0.1	n.d.	C (Sg, Sf)
Condamine (2)	8.7	41	23.vi.95	7.6[A]	6480	705	*0.3*	0.4	0.1	C (Sg, Sf)
				12.3[A]	10 270	900		n.d.	n.d.	C (Cp)
				18.5[A]	15 100	1179		n.d.	n.d.	C (Sg, Sf)
Emerald	7.8	69	4.vii.94	2.5	1930	100	*2.4*	4.4	0.2	C, M, T (Sg)
				6.7	6200	287		n.d.	n.d.	C, M, T (Sg)
			18.v.95	3.8	2910	109	*3.1*	3.2	1.5	C, M, T (Sg)
				9.3	8490	564		n.d.	n.d.	C, M, T (Sg, Sf)
				11.7	10 790	783		n.d.	n.d	C, M, T (Cp)
Capella	8.6	50	18.vii.95	3.1[A]	2570	89	*3.5*	1.5	2.7	C (Sg)
				6.6[A]	4810	487	*0.7*	*0.5*	*0.4*	C (Sg, Sf)
				10.8[A]	10 170	662	*0.4*	0.4	0.2	C (Cp)
			19.vi.96	2.8[A]	2440	39	*4.6*	5.7	1.8	C, M, T (Sg)
				7.0[A]	6470	271	*1.0*	1.1	0.5	C, M, T (Sg, Sf)

n.d., not detected. [A] Crops were grown in undisturbed soil cores placed in glasshouse.

of Australia. These recommendations are broadly based and may not fully account for all differences in climatic and soil factors across the extensive cropping regions. Also, information is lacking on the tolerance of chickpea, a common pulse of the subtropics.

The objective of this research was to investigate whether the choice of crop and time of sowing following applications of sulfonylurea herbicides can be improved using recommendations specific for the different soils and climates of the grain region of Queensland rather than the current plant-back recommendations. This paper reports on responses of sorghum, sunflower, and chickpea following applications of chlorsulfuron, triasulfuron, and metsulfuron-methyl at sites across this region. Relationships between seedling growth and plant-back, soil type, pH, clay content, cumulative temperature, and rainfall from spraying to sowing are investigated for these crops and herbicides, as well as chlorsulfuron concentration in soil at sowing.

Materials and methods

Sites

Crop response was measured in 29 field experiments at 17 sites over 4 seasons from 1994–95 to 1997–98. Sites were from Capella (23°S, 148°E) to Goondiwindi (28°S, 150°E), covering the geographical spread and 3 major soils (vertosols, sodosols, ferrosols) for dryland broadacre cropping in Queensland (Tables 1–3). The vertosol sites were located across the Darling and Western Downs of southern Queensland and on the Central Highlands of central Queensland, whereas the ferrosol sites were in the Burnett Region of south-eastern Queensland, and sodosol sites were on the South-West Downs of southern Queensland. Soil pH (1 : 5 soil : water) ranged from 5.5 to 9.0, and clay content from 17 to 72%. The sites had no residual herbicides applied within at least the previous 2 years.

Herbicides

Herbicides were applied to bare fallows using a boom mounted on a 4-wheel-drive all-terrain vehicle, with 110° flat fan nozzles delivering solutions at 60–100 L/ha and 200 kPa. Application was from mid-May to early August (Tables 1–3). Chlorsulfuron (as Glean, 750 g a.i./kg, DuPont), triasulfuron (as Logran, 714 g a.i./kg, Novartis), and metsulfuron-methyl (as Ally, 600 g a.i./kg, DuPont) were applied at the recommended rates of 15, 25, and 4.2 g/ha, respectively, and, in many experiments, at double rates.

Crops

Sorghum, sunflower, and chickpea were sown into treated and untreated soils (Tables 1–3) at different intervals after spraying. These plant-back periods ranged between 2 and 20 months for sorghum and sunflower in the chlorsulfuron treatments and between 2 and 9 months for the other herbicides. Chickpea was sown between 10 and 13 months. Crops were sown directly into field plots when rain or irrigation permitted. To increase the range of plant-backs, seedlings were also grown in undisturbed soil cores (20 cm depth, 10 cm diameter PVC tubes) in glasshouses. These cores were sampled at random from each plot (5–8 cores per plot for each crop to be sown in them), carefully transported back to a glasshouse, and then sown with seeds of sorghum and sometimes sunflower in summer, or chickpea in winter. After emergence, seedlings were thinned to 2 per tube, and soil was maintained near field capacity with regular overhead watering. Fertiliser was applied at sowing of crops in the field or glasshouse at rates based on soil type and nutrient analyses. Seedling shoot dry matter (SDM) was measured at 3 (summer) or 4 (winter) weeks after sowing in the field (g/2-m row) and glasshouse (g/2 plants). Grain yield at crop maturity was measured in most field plots. Rainfall and daily air temperatures were recorded, and cumulative rainfall and maximum temperatures were calculated for each plant-back. Rainfall includes all rain and irrigation up to sowing in the field and to time of core sampling, but not the added water for sowing in the cores.

Soil sampling and bioassays

At each sowing time, soil samples were collected from the chlorsulfuron treatment (15 g/ha) in the vertosol sites, and then air-dried (40°C for 18 h), sieved (5 mm), mixed thoroughly, and stored in a deep freeze (–20°C). The samples (10 per plot) were taken using a 5-cm-diameter tube from either 0–10 cm depth or 0–5 plus 5–15 cm depths. Chlorsulfuron concentrations in these samples were determined using a bioassay based on maize root growth suppression, and calculated using a logistic equation, as described by Walker and Robinson (1996).

Design and analyses

Experimental design was a randomised complete block with 3 replicates and with herbicides and rates as the treatments, all of which were

Table 2. Details of sites with sodosol soil, dates of spraying of chlorsulfuron (C), metsulfuron-methyl (M), triasulfuron (T), plant-backs for sowing of sorghum (Sg), sunflower (Sf), or chickpea (Cp), and cumulative temperature and rainfall between spraying and sowing

Site	Soil pH (1:5 water)	Clay content (%)	Dates of spraying	Plant-back (months)	Cumulative temperature (max. °C)	Rainfall (mm)	Herbicide (crop)
Goondiwindi (1)	7.1	34	26.vi.95	2.7[A]	1770	48	C (Sg, Sf)
				7.4[A]	6015	556	C (Sg, Sf)
				11.5[A]	9270	776	C (Cp)
				17.3[A]	13 400	989	C (Sg, Sf)
			5.vi.96	4.9[A]	3200	182	C, M, T (Sg)
				6.6	4850	262	C, M, T (Sg)
				13.2	10 310	686	C, M, T (Cp)
			18.vi.97	4.3[A]	2950	84	C, M, T (Sg)
				7.4[A]	6150	158	C, M, T (Sg)
Goondiwindi (2)	6.6	17	18.vi.97	4.3[A]	2970	135	C, M, T (Sg)
				8.2[A]	7070	385	C, M, T (Sg)

[A] Crops were grown in undisturbed soil cores placed in glasshouse.

Table 3. Details of sites with ferrosol soil, dates of spraying of chlorsulfuron (C), metsulfuron-methyl (M), triasulfuron (T), plant-backs for sowing of sorghum (Sg), sunflower (Sf), or chickpea (Cp), and cumulative temperature and rainfall between spraying and sowing

Site	Soil pH (1:5 water)	Clay content (%)	Dates of spraying	Plant-back (months)	Cumulative temperature (max. °C)	Rainfall (mm)	Herbicide (crop)
Kingaroy (1)	5.5	56	27.vii.94	3.0[A]	2270	36	C (Sg, Sf)
				6.0	5120	135	C (Sg, Sf); M, T (Sg)
				6.3[A]	5350	165	C (Sg)
				9.9	8380	443	C, M, T (Cp)
			1.viii.95	3.0[A]	2310	98	C (Sg, Sf)
				3.3	2550	123	C, M, T (Sg)
				6.2[A]	7130	722	C (Sg, Sf)
			21.vi.96	1.9[A]	1130	91	C, M, T (Sg)
				4.1[A]	2840	239	C, M, T (Sg)
			11.vii.97	1.6[A]	1020	28	C, M, T (Sg)
				2.7[A]	1870	110	C, M, T (Sg)
				3.9[A]	2780	213	C, M, T (Sg)
Kingaroy (2)	6.0	60	27.vii.94	3.0[A]	2270	46	C (Sg, Sf)
				5.4	4640	173	C (Sg, Sf); M, T (Sg)
				6.2[A]	5350	230	C (Sg)
				9.9	8380	444	C, M, T (Cp)
			1.viii.95	3.0[A]	2310	88	C (Sg, Sf)
				6.2[A]	7130	829	C (Sg, Sf)
Kingaroy (3)	6.8	58	21.vi.96	1.9[A]	1130	91	C, M, T (Sg)
				4.1[A]	2840	239	C, M, T (Sg)
				5.8	4450	351	C, M, T (Sg)

[A] Crops were grown in undisturbed soil cores placed in glasshouse.

duplicated for sowing of the different crops. Plots size varied with site, crop, and season, but the majority of plots were 10–15 m by 2.5–5 m. Plots were maintained weed-free in the fallow with applications of glyphosate, and were not cultivated between spraying and sowing.

Seedling SDM and grain yield for each crop and site were subjected to separate analyses of variance. Seedling growth (SDM as percentage of untreated) was then compared graphically between crops grown in the field and glasshouse over the range of plant-backs. As well, sorghum seedling growth in the field and glasshouse was compared by simple linear regression with grouping for plant-back of <10 months in chlorsulfuron treatments in vertosols.

Using the combined data from field and glasshouse, relationships of seedling growth (SDM as percentage of untreated) as a function of plant-back and cumulative temperature, as well as measured chlorsulfuron concentration in vertosols, were tested by various regression analyses. Chlorsulfuron concentrations were compared for the 0–10 cm depth, using data measured for this depth or estimated from the 0–5 and 5–15 cm depth measurements. Linear ($Y = A + BX$), exponential ($Y = A + BR^X$), and logistic ($Y = A + C/[1 + \exp(-B(X - M))]$) equations were fitted to the data. For the logistic equation, X is the logarithm of the explanatory variate, A and $A + C$ are lower and upper asymptotes, M is log (ID_{50}), and B is proportional to slope at ID_{50}, the dose for 50% inhibition in seedling growth. GENSTAT 5 statistical package (2nd edn, 1996) was used for these analyses.

Crop responses to each herbicide were analysed first using data from all sites, and then separately for each soil type. The sorghum and sunflower responses to chlorsulfuron in vertosols were analysed for plant-backs of 2–9 months and 2–20 months. Best fit was judged based on uniformity of variance in graphed residual values, standard errors of the parameters, and r^2 values. Variations in residuals from the logistic relationships between sorghum growth and plant-back were compared with soil pH, clay content, temperature, and rainfall by regression analyses. As well, the linear relationships between sorghum growth and plant-back for each herbicide were compared with variations in soil pH, clay content, temperature, and rainfall by multiple regression analyses. The rainfall variate was compared firstly with measured rain and secondly with the inclusion of an extra 50 mm for the soil core data, as an estimate of volume of water added prior to sowing.

Analyses of the above relationships used only crop data from herbicide treatments at the recommended rate. However, the comparison between seedling growth and yield used the data from treatments with recommended and double rates.

Results

Field and glasshouse growing environments

Seedling growth (SDM as % of untreated) appeared to be either similar for the same plant-back, or slightly less for data collected from the field compared with data from soil cores. Sorghum responses to chlorsulfuron in vertosols were from a mixture of field and soil core data (Fig. 1). The linear trends for plant-back of <10 months showed that sorghum SDM_{field} was on average 9% less than $SDM_{soil\ core}$, but the simple linear regression analysis with groups (field and soil core) was not significant (P = 0.53). The majority of chickpea responses to all herbicides (Fig. 2) and sorghum following metsulfuron-methyl and triasulfuron in vertosols (Fig. 3)

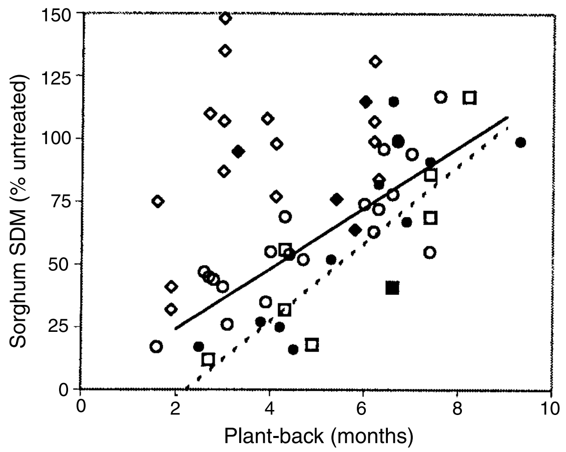

Fig. 1. Seedling sorghum response (SDM as % of untreated) when sown at different plant-backs (PB) up to 10 months in chlorsulfuron treated vertosol (circle), ferrosol (diamond), and sodosol soils (square). Crops were grown in the field (closed symbols) or in soil cores in the glasshouse (open symbols). Lines are fitted linear regressions for vertosols (continuous): SDM(V) = 12.8PB – 4.1 (r^2 = 0.66); and sodosols (dotted): SDM(S) = 15.5PB – 34.7 (r^2 = 0.66).

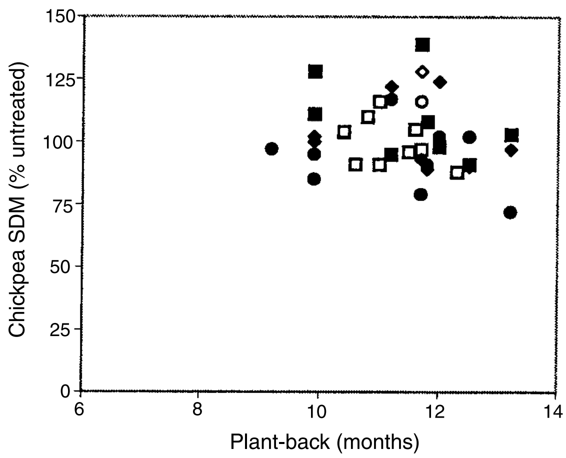

Fig. 2. Seedling chickpea response (SDM as % of untreated) when sown at different plant-backs in chlorsulfuron (square), metsulfuron-methyl (diamond), and triasulfuron (circle) treated soil. Crops were grown in the field (closed symbols) or in soil cores in the glasshouse (open symbols). Data were combined for vertosol, ferrosol, and sodosol soils.

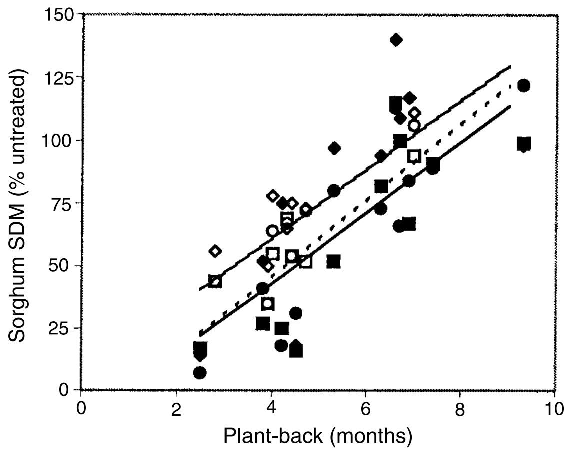

Fig. 3. Seedling sorghum response (SDM as % of untreated) when sown at different plant-backs (PB) up to 10 months in chlorsulfuron (square), metsulfuron-methyl (diamond), and triasulfuron (circle) treated vertosol soils. Crops were grown in the field (closed symbols) or in soil cores in the glasshouse (open symbols). Lines are fitted linear regressions for chlorsulfuron (continuous): SDM(C) = 14.1PB – 13.2 (r^2 = 0.65); metsulfuron-methyl (serrated): SDM(M) = 13.7PB + 6.3 (r^2 = 0.53); and triasulfuron (dotted): SDM(T) = 15.2PB – 15.0 (r^2 = 0.71).

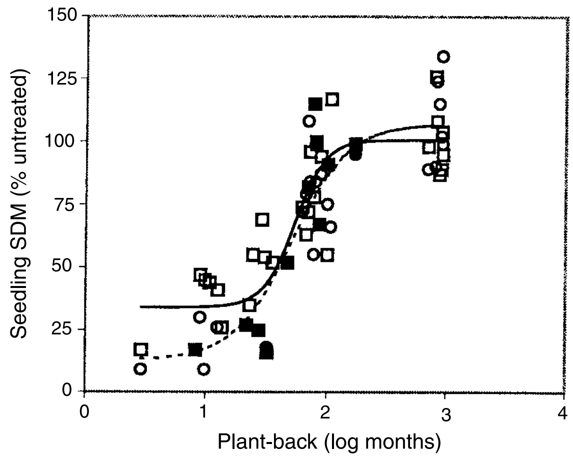

Fig. 4. Seedling sorghum (square) and sunflower (circle) response (SDM as % of untreated) when sown at different plant-backs (PB) up to 20 months in chlorsulfuron-treated vertosol soils. Crops were grown in the field (closed symbols) or in soil cores in the glasshouse (open symbols). Lines are fitted non-linear regression using logistic equations for sorghum (continuous): SDM(Sg) = 34.1 + 66.6/(1 + exp[–7.87(logPB – 1.73)]) (r^2 = 0.74); and sunflower (dotted): SDM(Sf) = 12.7 + 94.3/(1 + exp[–4.26(logPB – 1.70)]) (r^2 = 0.78).

were from the field, and there were no obvious visual differences between growing environments. However, crop responses in sodosols (Fig. 1) and sorghum and sunflower responses in vertosols for plant-back of >10 months (Fig. 4) were nearly all from soil core data.

Sorghum and chlorsulfuron

Seedling growth in chlorsulfuron-treated soil was extremely variable for plant-backs of <10 months across all sites (Fig. 1). At plant-back of approximately 3 months, SDM ranged from 10 to 150% of the untreated. Fit of the linear (r^2 = 0.19) and other tested models was poor, although the linear relationship improved with inclusion of the soil pH variate (r^2 = 0.46).

Seedling response differed substantially among the different soils. In ferrosols, response was largely unaffected by plant-back, and SDM was not significantly reduced following a minimum plant-back of 3 months (Fig. 1) and approx-

Table 4. Parameters for linear equations fitted to sorghum and sunflower seedling growth (SDM as % of untreated) when crops were sown in chlorsulfuron, triasulfuron, and metsulfuron-methyl treated vertosol (V) and sodosol (S) soils and compared with plant-back for 2–10 months and cumulative temperature

A is intercept, *B* is slope with standard errors (s.e.) in parentheses, ID_{10} and ID_{25} are calculated values of the explanatory variate for 10 and 25% reduction in SDM (respectively)

Linear relationship between sorghum SDM(V) and plant-back was analysed using all data (n = 31) and using only data common with metsulfuron-methyl and triasulfuron treatments (n = 19)

Response variate	Explanatory variate	*A* (s.e.)	*B* (s.e.)	r^2	n	ID_{10}	ID_{25}
			Chlorsulfuron				
Sorghum SDM(V)	Plant-back (months)	–4.1 (9.2)	12.8 (1.7)	0.66	31	7.4	6.2
	Cumulative temp (max. °C)	6.9 (7.6)	0.0136 (0.0017)	0.67	31	6100	5000
	Plant-back (months)	–13.2 (13.6)	14.1 (2.4)	0.65	19	7.3	6.3
	Cumulative temp (max. °C)	3.0 (10.6)	0.0141 (0.0024)	0.67	19	6200	5100
Sorghum SDM(S)	Plant-back (months)	–34.7 (24.4)	15.5 (4.06)	0.66	8	8.0	7.1
	Cumulative temp (max. °C)	–18.8 (16.5)	0.0166 (0.0035)	0.76	8	6550	5650
Sunflower SDM(V)	Plant-back (months)	–11.9 (12.8)	12.8 (2.1)	0.72	15	7.9	6.8
	Cumulative temp (max. °C)	–0.4 (10.7)	0.0134 (0.0022)	0.73	15	6750	5600
			Triasulfuron				
Sorghum SDM(V)	Plant-back (months)	–15.0 (12.9)	15.2 (2.3)	0.71	19	6.9	5.9
	Cumulative temp (max. °C)	5.9 (11.3)	0.0143 (0.0026)	0.66	19	5850	4800
			Metsulfuron				
Sorghum SDM(V)	Plant-back (months)	6.3 (16.9)	13.7 (3.1)	0.53	19	6.1	5.0
	Cumulative temp (max. °C)	25.9 (14.5)	0.0128 (0.003)	0.46	19	5000	3850

imately 2300°C and 100–150 mm rainfall (Table 3). No tested model fitted the SDM data, and this response in the ferrosols with plant-back or cumulative temperature did not improve with the addition of the soil and climatic variates.

In contrast, responses in the vertosols and sodosols were highly influenced by plant-back and cumulative temperature. Seedling growth increased linearly with plant-back of 2–9 months (Fig. 1) and with cumulative temperature (Table 4). The linear relationships with cumulative temperature tended to be similar to, or better than, with plant-back. Seedling growth tended to be affected more in sodosols than in vertosols for the same plant-back. The estimated ID_{25} values were 6.2–6.3 months and 5000–5100°C in vertosols and 7.1 months and 5650°C in sodosols.

Over longer plant-backs up to 20 months, response in vertosols was best explained with a logistic model (Figs 4, 5). Goodness of fit for the logistic equations was similar for the relationships with plant-back, cumulative temperature, or chlorsulfuron residue in surface soil. The estimated ID_{25} values were 6.0 months and 4700°C when the surface had 0.9 ng chlorsulfuron/g soil (Table 5). The ID_{10} and ID_{25} estimates were slightly less than those calculated using the linear model for plant-back of 2–9 months (Table 4). None of these relationships improved with the addition of the soil and climatic variates.

Sorghum and triasulfuron

As with chlorsulfuron, seedling growth in triasulfuron-treated soil was extremely variable for plant-backs of <10 months across all sites (data not presented). Fit of the linear (r^2 = 0.33) or other models was poor, although the linear relationship improved with inclusion of the soil pH variate (r^2 = 0.57).

Responses differed substantially between ferrosols and vertosols. Response in the ferrosols was largely unaffected by plant-back, and SDM was not significantly reduced with a minimum plant-back of 3 months and approximately 2300°C and 100–150 mm rainfall. No tested model fitted the SDM data, and this response in the ferrosols with plant-back

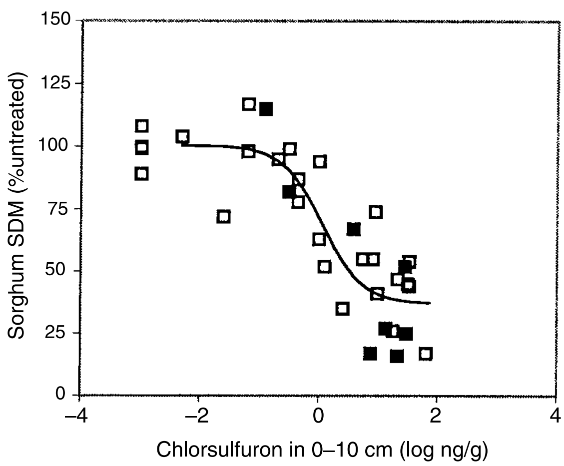

Fig. 5. Relationship between seedling sorghum SDM (% untreated) and measured chlorsulfuron concentrations (CC) in the surface soil (0–10 cm) at time of sowing as measured by bioassay. Crops were grown in the field (closed symbols) or in soil cores in the glasshouse (open symbols). The line is fitted non-linear regression using a logistic equation: SDM(Sg) = 37.0 + 63.4/(1 + exp[2.93(logCC – 0.061)]) (r^2 =0.74).

Table 5. Parameters for logistic equation fitted to sorghum and sunflower seedling growth (SDM as % of untreated) to plant-back for 2–20 months, cumulative temperature, and chlorsulfuron residue in surface 10 cm at sowing in vertosol soil

A is lower asymptote, *A*+*C* is upper asymptote, *B* is slope at ID_{50}, and *M* is log (ID_{50}) with standard errors (s.e.) in parentheses, as well as the calculated value of the explanatory variate for 10 and 25% reduction in SDM (ID_{10} and ID_{25}, respectively)

Response variate	Explanatory variate	*A*	*C*	*B* (s.e.)	*M* (s.e.)	r^2	*n*	ID_{10}	ID_{25}
Sorghum SDM	Plant-back (months)	34.1	66.6	7.87 (3.00)	1.73 (0.07)	0.74	38	7.0	6.0
	Cumulative temp (max. °C)	32.4	69.5	5.01 (1.85)	8.36 (0.11)	0.74	38	5850	4700
	Residue (ng/g in 0–10 cm)	37.0	63.4	–2.93 (1.42)	0.061 (0.19)	0.74	28	0.6	0.9
Sunflower SDM	Plant-back (months)	12.7	94.3	4.26 (2.24)	1.70 (0.13)	0.78	22	7.8	6.4
	Cumulative temp (max. °C)	10.7	98.7	3.03 (1.68)	8.35 (0.17)	0.81	22	6750	5200

did not improve with the addition of the soil and climatic variates.

As with chlorsulfuron, crop response in vertosols was highly influenced by plant-back and cumulative temperature. Seedling growth increased linearly with plant-back of 2–9 months (Fig. 3) and cumulative temperature (Table 4). The linear relationship tended to be slightly better with plant-back than cumulative temperature, and did not improve with the addition of climatic or soil variates. Sorghum growth tended to be less affected in triasulfuron-treated soil than chlorsulfuron for the same plant-back. The estimated ID_{25} value following triasulfuron was 0.4 month shorter than for chlorsulfuron.

Response in vertosols and sodosols appeared similar, but data were only limited from sodosol sites (data not presented).

Sorghum and metsulfuron-methyl

Again, crop response was variable with plant-back across all sites (data not presented) and fit of linear (r^2 = 0.17) or other tested models was poor. However, unlike for chlorsulfuron and triasulfuron, this did not improve with addition of the soil pH variate.

Again, seedling response was very different between the ferrosols and vertosols. Seedling growth in the ferrosols was unaffected by any tested plant-back, and SDM was not significantly reduced following a minimum plant-back of 2 months and approximately 1200°C and 100–150 mm rainfall (data not presented).

Seedling growth in vertosols increased linearly with plant-back (Fig. 3) but the relationship was slightly more variable than for the other herbicides (Table 4). These relationships did not improve with the climatic and soil variates. Sorghum growth tended to be less affected following metsulfuron-methyl than triasulfuron and chlorsulfuron for the same plant-back. The estimated ID_{25} following metsulfuron-methyl was 1.3 months shorter than for chlorsulfuron.

Seedling growth appeared to be affected more in sodosols than vertosols for the same plant-back, but data were only limited from sodosol sites (data not presented).

Sunflower

As with sorghum, when data for all sites were compared, seedling growth in chlorsulfuron-treated soils was also very variable for plant-backs at <10 months (data not presented). The linear relationship between crop response across all sites and plant-back of 2–9 months (r^2 = 0.18) was poor as with other fitted models. However, the linear relationship improved substantially with the addition of the soil pH variate (r^2 = 0.64), but not with other soil and climatic variates.

As with sorghum, sunflower seedling response differed between the major soils. In ferrosols, seedling growth was largely unaffected by plant-back, and SDM was not significantly reduced following a minimum plant-back of 3 months and approximately 2300°C and 100–150 mm rainfall (data not presented). No model could be fitted to the data, and this response in seedling growth in the ferrosols with plant-back or cumulative temperature did not improve with the addition of the soil and climatic variates.

In vertosols, seedling response to chlorsulfuron was strongly related to plant-back of 2–9 months (r^2 = 0.72) and to cumulative maximum temperature (r^2 = 0.73) (Table 4). These linear relationships did not improve with the addition of other soil or climatic variates. Over longer plant-backs, sunflower response in vertosols was best explained with a logistic model (Fig. 4). Goodness of fit for the logistic equations was slightly better with cumulative temperature than plant-back. However, unlike for sorghum, the logistic model could not be fitted to the measured chlorsulfuron concentrations. The estimated ID_{10} values for plant-back and cumulative temperature were very similar from the linear (Table 4) and logistic equations (Table 5) and tended to be greater than for sorghum. None of these relationships improved with the addition of the soil and climatic variates.

There were insufficient data for comparing sunflower response in metsulfuron-methyl and triasulfuron treated vertosols, and to all herbicides in ferrosols and sodosols.

Chickpea

Seedling growth was unaffected following chlorsulfuron, triasulfuron, or metsulfuron-methyl at any site (Fig. 2). This was following plant-backs of 10–13 months and approximately 8400–10 800°C and 450–1200 mm rainfall (Tables 1–3).

Grain yield

Crops, which had seedling biomass reductions of 25% or less from sulfonylurea residues, subsequently recovered without any significant grain yield reductions in 101 of the 102 treatments that were grown to maturity (Fig. 6). The exception was from an experiment with a 75% coefficient of variation. The majority (88%) of the treatments with 26–50% seedling biomass reductions also had no significant yield reductions. However, most crops with >50% seedling biomass reductions had substantial reductions in yield.

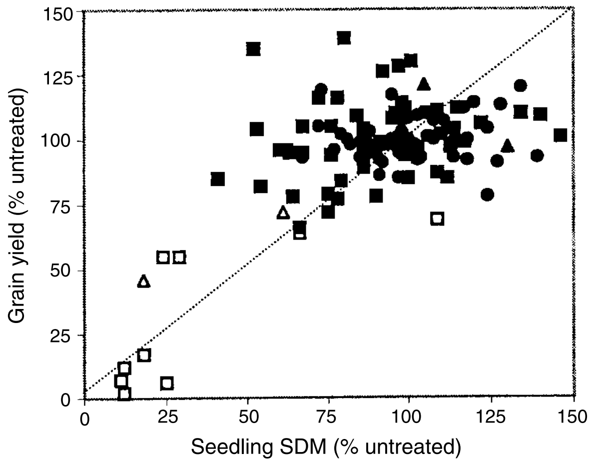

Fig. 6. Comparison of seedling SDM (% untreated) grown in sulfonylurea-treated soils with grain yield (% untreated) of sorghum (square), sunflower (triangle), and chickpea (circle). Open symbol is for grain yield significantly less than untreated, and closed symbol is for not significantly different. Data include crop response following recommended and double rates of application. Line drawn is for 1 : 1 relationship.

Comparison of predicted with measured crop response

Data from this research have enabled the development of relationships for predicting seedling crop responses following sulfonylurea applications in vertosol and sodosol soils based on plant-back, cumulative temperature, and measured chlorsulfuron residues. There were no significant seedling biomass reductions at, or greater than, the estimated ID_{10} values. However, there were biomass reductions of 28–45% between the estimated ID_{10} and ID_{25} plant-back or cumulative temperature values for 7 sowings. Most of these biomass reductions were not significant, and all except one had chlorsulfuron residues greater than the estimated ID_{25} value of 0.9 ng/g soil. These sites received less than 300 mm rainfall and/or had soil pH > 8.5.

Discussion

Crop response to sulfonylurea residues was very variable across the grain region of Queensland. However, improved and more specific recommendations have been developed for safe re-cropping for the different soils and climates of this region following applications of chlorsulfuron, triasulfuron, and metsulfuron-methyl, and in many instances these differ and are shorter than current plant-back recommendations.

Sorghum and sunflower can be safely sown in the second summer irrespective of soil or climatic factors, and this is consistent with the current recommendations (Parsons 1995). In contrast to the current recommendations, there are opportunities for double cropping with sorghum and sunflower following sulfonylurea applications in the previous winter. These are dependent on the major factors influencing sulfonylurea degradation rates and their availability for plant uptake.

Soil pH and soil type were important factors that influenced sorghum and sunflower responses following sulfonylurea applications. The importance of soil pH was evident from the improved relationships between seedling growth and plant-back with the addition of this soil variate, at least for chlorsulfuron and triasulfuron. Also, crop response was influenced much less by plant-back in the acidic ferrosols than in the alkaline vertosols. This was likely due to the rapid degradation of the sulfonylurea residues in soils with decreasing pH (Walker *et al*. 1989; Sarmah *et al.* 1998, 1999), but may also be due to the residues being less available for plant uptake in the ferrosols. Initial activity of chlorsulfuron residues has been shown to be comparatively low in the ferrosols (Walker *et al.* 1994), which may be due to adsorption to iron oxides (Borggaard and Streibig 1988), high contents of which are found in ferrosols. As well, soil pH does not explain the differences in crop response in the sodosols and vertosols. Seedling growth tended to be affected more in the neutral sodosols than in the alkaline vertosols for the same plant-back. Churchett *et al.* (1999) have also found that lucerne growth was affected more in sodosols than in vertosols with similar soil pH following application of sulfonylureas. This may be due to variations in soil clay content, which can have significant effect on crop response to the sulfonylurea residues. Walker *et al.* (1994, 1997) have shown that chlorsulfuron was more available for plant uptake in the lighter textured vertosols (grey clays) than the heavier textured soils (black earths), and this influenced the effectiveness and duration of weed control. Soil texture appears to influence crop response to sulfonylurea residues, and this needs to be taken into consideration with predicting safe re-cropping.

Temperature was also an important factor influencing crop response to the sulfonylurea residues, which is consistent with herbicide degradation studies (Walker and Brown 1983; Beyer *et al.* 1987; Oppong and Sagar 1992) as well as other field studies (Anderson 1985). This was evident with the good relationships between seedling growth and cumulative temperature, which was often a better explanatory variate than plant-back. This may be due to plant-back not taking into account seasonal differences between years, differences in climates across the grain region, and differences in the application window. The short re-cropping intervals, as suggested by this research, are likely due to the warmer winters of the subtropics compared with southern Australia. Mean winter maximum is 23°C at Emerald in central Queensland compared with 14°C at Dooen in western Victoria, where Black *et al.* (1999) have shown that sulfonylurea residues persist for long periods. Consequently, it is important that plant-backs be qualified with cumulative temperature for that period between application and sowing.

In contrast to the effects of temperature, rainfall after application seemed to have only a small influence on the safety of re-cropping. Obviously, some soil water is essential for microbial and chemical degradation, and it appears that a minimum rainfall of approximately 100–150 and 300–400 mm in ferrosols and vertosols, respectively, was needed for degradation of sulfonyulurea residues to levels safe for sowing sorghum in the subtropics. In Italy, Vicari *et al*. (1994) found that rainfall above 500 mm had minimal effect on field persistence of chlorsulfuron and triasulfuron in their alkaline soils. In central Queensland, Osten and Walker (1998) found that only 80 mm of fallow rain was needed for sufficient degradation of metsulfuron-methyl for safe sowing of sunflower and sorghum. As well, Osten and McCosker (1999) showed that only 40 mm of fallow rain was required for safe sowing of chickpea in the same season. The only modest influence of rainfall also agrees with Oppong and Sagar (1992), who found that degradation rates of triasulfuron in the laboratory were influenced more by temperature than variations in soil water. The variability in the timing and frequency of rainfall events would also contribute to lack of significance for this climate variate on crop response.

Sorghum seemed less susceptible to chlorsulfuron residues than sunflower, which was consistent with the measured sensitivity of these crops to residues in a soil-free system (Jettner *et al*. 1999). The ID_{30} value of sunflower was 0.42 μg chlorsulfuron/L compared with 0.86 for sorghum, which is very similar to the estimated ID_{25} value of 0.9 ng chlorsulfuron/g soil from the field data.

Chickpea can be safely sown in the following winter irrespective of soil factors, which is additional information not currently on chlorsulfuron labels. This is consistent with what has been found previously by Osten and Walker (1998).

Seedlings, when exposed to low levels of sulfonylurea residues, were able to recover from initial slight damage without any adverse effects on yield. Seedlings were able to withstand biomass reductions of up to 25%, and then recover fully, presumably when the root system expanded below that part of the soil profile containing the majority of the remaining residues, which would continue to degrade with time. In the subtropical grain region, which has summer-dominant rainfall, movement of chlorsulfuron residues below the surface 20 cm was minimal following repeated annual applications (Walker and Robinson 1996) or not detectable following a single application (S. R. Walker unpubl. data). This is in contrast to results from similar soils receiving winter-dominant rainfall in Victoria, where substantial sulfonylurea residues were detected at 40–60 cm depths (Black *et al.* 1999).

The technique of measuring seedling growth in soil cores seemed a useful and relatively simple method to be able to collect crop response data over a greater range of re-cropping intervals and sites. The similar response is likely due to the root system of the seedling plant being exposed to a herbicide distribution profile in the undisturbed soil core similar to that in the field. This technique would not be appropriate in regions with greater mobility of the sulfonylureas, as in southern Australia.

In conclusion, there is considerable scope for use of sulfonylurea herbicides in the opportunistic cropping systems of the subtropical grain region. This paper outlines alternative plant-backs and predictive relationships specific for different soils and climates of Queensland, when a range of crops can be safely sown following sulfonylurea applications. These more specific recommendations will greatly increase the safety and flexibility of re-cropping following the use of sulfonylurea herbicides in this region.

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