Influence of soil water deficit on performance of foliar-applied herbicides for wild oat and annual ryegrass in wheat

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Summary

The effect of soil water deficit on dose-responses of the foliar-applied, wheat selective herbicides, diclofop-methyl, fenoxaprop-p-ethyl, tralkoxydim, clodinafop-propargyl and flamprop-methyl for wild oat (*Avena sterilis*), and diclofop-methyl, tralkoxydim and clodinafop for annual ryegrass (*Lolium rigidum* Gaud.) was examined in the glasshouse and field. Prolonged periods of soil water deficit (i.e. from before herbicide application until the end of tillering) reduced efficacy of the three ryegrass herbicides in a similar way, and control by diclofop-methyl was greater than by tralkoxydim or clodinafop under all conditions. Control of wild oat by diclofop-methyl or fenoxaprop-p-ethyl was less than that by tralkoxydim, especially under dry conditions, whereas flamprop-methyl and clodinafop were less effective under all conditions. The influence of soil water deficit, either before or after herbicide application, caused herbicide dose-responses for diclofop-methyl and fenoxaprop-p-ethyl in wild oat that were intermediate between those for the prolonged dry or wet treatments. This was also observed for all herbicides in annual ryegrass. In the field, wild oat was completely killed by the recommended rates of either diclofop-methyl at 0.752 kg a.i. ha^{-1} or tralkoxydim at 0.20 kg a.i. ha^{-1} under dry or wet conditions at the time of application. Under prolonged dry conditions, the tolerance of wheat to both herbicides was severely reduced in the field. The practical implication of this work is that farmers are more likely to experience unreliable control of wild oat or annual ryegrass with some foliar-applied herbicides, especially at low rates of application and when conditions are dry.

Introduction

Wild oats (*Avena sterilis* and *Avena fatua*) and annual ryegrass (*Lolium rigidum* Gaud.) are important grass weeds of wheat in the winter cropping region of Australia and a range of selective post-emergence herbicides are available for their control. The recommended rates of application (1×R) aim to control weeds without causing crop damage over the range of environments where the herbicides are to be applied. However, variability of the weather, both before and after application, is a major cause of unreliable herbicide performance even at recommended rates of application (Caseley 1987, Kudsk and Kristensen 1992). In addition, when farmers use application rates below those recommended to reduce the high costs of grass weed control, the risk of poor weed control is even greater.

In Australia, circumstantial evidence suggests that soil water deficit is an important factor affecting herbicide activity. A survey of farmers' spraying results by the Kondinin Group in 1991 found that 66% of respondents experienced poorer than expected weed control and blamed this on prolonged dry weather before spraying (Peter Cooke personal communication). In Canada, Wilcox *et al.* (1987) found that low soil moisture reduced the activity of some foliar-applied wild oat herbicides. Furthermore, herbicide labels recommend not to apply chemicals when the crop or weed are drought stressed (Anon. 1992). However, there are no published Australian data concerning the effect of soil moisture on the control of wild oat or annual ryegrass by foliar herbicides or its impact on the tolerance of wheat to these herbicides.

The experiments described here, aimed to determine the influence of dry soil conditions before and after spraying on dose-responses of herbicides for wild oat and annual ryegrass control in wheat. This information would be useful for two main reasons. Firstly, in explaining the impact of soil water deficit on variable herbicide performance from different sites and seasons. Secondly, for increasing the precision of field recommendations and altering applications rates for different conditions. The herbicides chosen were the main ones registered for control of these weeds in wheat, except clodinafop which was undergoing development.

Materials and methods

Glasshouse experiments

Two experiments were done in the glasshouse, one in spring 1992 for wild oat, and one for annual ryegrass in spring 1993. The glasshouse was cooled during the day to 20°C, and heated at night so that the temperature did not fall below 3°C.

Photosynthetic photon flux density varied from 200 to 1000 mol m^{-2} s^{-1}, similar to normal day levels for that time of year in the local environment. No additional lighting was used in the glasshouse. Plants were grown in soil in plastic pots (15 cm diameter: 0.9 L volume). Pots were filled with a local silty clay loam from the Agricultural Research Institute, Wagga Wagga, New South Wales, with the following characteristics: 30% clay, 25% silt and 45% sand; pH of 4.4 (1:5, 0.01M $CaCl_2$); 1.8% organic matter. The soil was collected from the top 150 mm of the soil profile and dried at 40°C. Wild oat (*Avena sterilis*) seed collected from the Forbes area in 1988 with 50% viability, was sown uniformly at 20 seeds per pot and emerged plants were thinned to eight well-spaced plants per pot 21 days after sowing. Annual ryegrass (commercial seed grown in the Wagga Wagga area) was sown at 12 plants per pot and thinned to 6 after emergence.

Both experiments had a split-split plot design with four replicates of the following treatments: herbicides as the main plots (five for wild oat and three for annual ryegrass, four soil moisture treatments as the subplots, and five herbicide rates as the sub-subplots. This design was chosen for ease of management and to ensure the greatest statistical precision was achieved between the watering treatments.

Initially, all pots were maintained close to 100% available soil moisture (100% ASM) by addition of water to the required gravimetric weight. Seven days after emergence water was withheld or added to the pots to achieve the following four soil moisture treatments:

i. 'wet', maintained close to 100% ASM until harvest at the end of tillering,

ii. 'dry', maintained close to 50% ASM until harvest,

Table 1. Rates of herbicide (g active ingredient ha^{-1}) for control of wild oat and annual ryegrass. Rates chosen are a proportion of the manufacturers' recommended (1×R) rate.

Weed/herbicide	0.25×R	0.50×R	1×R	2×R
Wild oat				
Clodinafop	5	10	21	42
Tralkoxydim	50	100	200	400
Diclofop-methyl	188	376	752	1500
Fenoxaprop-p-ethyl	10	21	41	83
Flamprop-methyl	113	225	450	900
Annual ryegrass				
Clodinafop	12	24	48	97
Tralkoxydim	50	100	200	400
Diclofop-methyl	188	376	752	1500

iii.'dry/wet', dry until herbicide application at the 3-leaf stage of growth followed by wet until harvest, and

iv.'wet/dry', wet until herbicide application followed by dry until harvest.

Herbicides were applied by pot sprayer with flat fan nozzles which delivered 125 L ha^{-1} at 170 kPa at the 3-leaf stage of weed growth. The application rates were an unsprayed control and a range of rates of active ingredients of each herbicide. Equivalent rates were based on the manufacturers' recommended (1×R) rates (Table 1). The herbicides used in wild oat were clodinafop-propargyl (plus safener, 75g L^{-1} cloquintocet-mexyl), tralkoxydim (plus Ulvapron, 855g L^{-1} petroleum oil, at 0.75% v/v), diclofop-methyl (plus Agral 600, nonyl phenol ethylene oxide condensate, a non-ionic wetting agent, at 0.25% v/v), fenoxaprop-p-ethyl and flamprop-methyl. The herbicides used in annual ryegrass were clodinafop-propargyl (plus safener, 75g L^{-1} cloquintocet-mexyl), tralkoxydim (plus Ulvapron, 855g L^{-1} petroleum oil, at 0.75% v/v) and diclofop-methyl (plus Agral 600, nonyl phenol ethylene oxide condensate, a non-ionic wetting agent, at 0.25% v/v).

Per cent survival of weed (S) based on plant number per pot was scored from 0 to 100, with 0 representing no plants surviving (i.e. complete kill) and 100 representing full survival (i.e. no effect) at the end of tillering. Dose-response curves were fitted by the logistic dose-response model

$$S = \frac{a}{1 + \left(\frac{r}{b}\right)^c}$$

where the a estimates the zero herbicide dose response (i.e. 100% survival), b is the half-effect parameter or ED_{50}, c is the shape parameter of the curve, and r is the rate of herbicide (as a proportion of the 1×R).

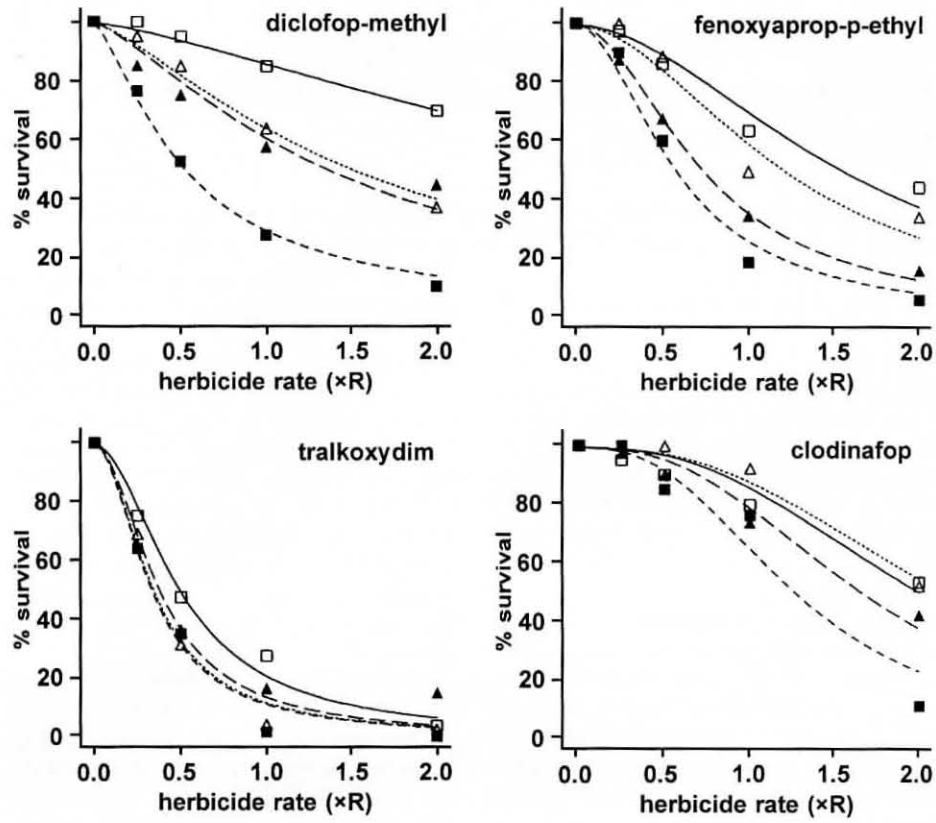

Figure 1. Response (% survival) of wild oat to foliar-applied herbicides under 4 soil moisture treatments:
i. 'wet' ■, maintained close to 100% ASM until harvest at the end of tillering,
ii. 'dry' □, maintained close to 50% ASM until harvest,
iii. 'dry/wet' △, dry until herbicide application at the 3-leaf stage of growth followed by wet until harvest, and
iv. 'wet/dry' ▲, wet until herbicide application followed by dry until harvest.

Field experiment

The experiment was conducted in the field under a rainshelter in 1993 at the Agricultural Research Institute at Wagga Wagga. Plots were 2 m long by 1.2 m (6 rows) wide. Wheat cv. Dollarbird was sown over the whole experimental area using a cone seeder on 5 May 1993 at a seeding rate of 55 kg ha^{-1} with superphosphate at 80 kg ha^{-1}. The seedbed was moist. Wild oat (the same seed as used in the glasshouse experiment) was hand-broadcast (29 g seed per plot) over the experimental area and raked-in immediately after the crop was sown. To reduce dormancy and promote germination percentage, wild oat seeds were individually pricked with a pin and soaked in a 0.1% (w/v) gibberellic acid solution for one hour and then allowed to dry one day prior to sowing. Crop and wild oat establishment was recorded three weeks after crop and weed emergence by counting wheat number in two 1 m row lengths and wild oat number in two 0.1 m^2 quadrats per plot.

The experimental design was a split-plot with three replicates of the following treatments: three herbicide treatments as the main plots (to facilitate herbicide application) and four soil moisture treatments as the subplots.

The four soil moisture treatments were the same as in the glasshouse experiments. These treatments were achieved by using the rainshelter immediately after sowing to prevent rain getting onto the experimental area. Water was applied to the wet treatments by irrigation as required. Volumetric water content of the soil was monitored using time domain reflectometry (TDR) (Anon. 1992) probes placed horizontally in the soil at depths of 0.1 m, 0.3 m and 0.5 m in all the plots of two replicates one week after sowing. ASM was calculated throughout the experiment.

The relative leaf water content of wild oat was estimated (Turner 1981) just before herbicide application, to evaluate it as a potential quick and simple method for farmers to estimate plant water status and relate this to herbicide performance.

The herbicide treatments were the manufacturers' 1×R rate: diclofop-methyl at 752 g ha^{-1} a.i. plus Agral 600 at 0.25% v/v) and tralkoxydim at 200 g ha^{-1} a.i. (plus Ulvapron adjuvant at 0.75% v/v) applied at the 4-leaf stage of wheat growth (wild oat at 3-leaf), plus an unsprayed control. The herbicides were applied on 25 June using a propane-powered, hand-held boom sprayer at a pressure of 130 kPa in 112 L ha^{-1} of water.

The rainshelter was removed on 26 July at the early stem elongation growth stage of the wheat, and rainfall was then allowed on the experimental area until harvest at anthesis on 23 September. Wheat height, tiller number per square metre and above-ground dry matter (DM) of both crop and wild oat (remaining in the untreated controls) was estimated from a 0.25 m^2 quadrat cut from each plot at anthesis. DM was the weight of plant material dried at 80°C for 48 hours.

The data were analysed using a spatial procedure and significance of effects was determined using the saturated spatial error model (Gleeson and Cullis 1987).

Results

Glasshouse experiment: wild oat

Wild oat foliage became yellow in all herbicide treatments (except flamprop-methyl) within three days of application when conditions were wet before application, whereas symptoms were much slower to develop in plants that were grown under soil water deficit. The severity of symptoms in descending order at equivalent rates was tralkoxydim > fenoxaprop-p-ethyl > diclofop-methyl > clodinafop.

The dose-responses fitted for each herbicide are in Figure 1. The shape parameters (± standard error) were 1.386 (0.125) for diclofop-methyl, 1.914 (0.146) for fenoxaprop-p-ethyl, 1.908 (0.150) for tralkoxydim, and 2.619 (0.272) for clodinafop. Flamprop-methyl gave very poor control of wild oat, and as no model was adequately fitted, the data are not presented. The ED_{50} values are in Table 2.

The performance of both diclofop-methyl and fenoxaprop-p-ethyl decreased under conditions of soil water deficit relatively more than that of tralkoxydim, which gave the most effective control under all conditions. For example, in the wet treatment the ED_{50} for diclofop-methyl or fenoxaprop-p-ethyl was approximately 0.55, compared with 3.77 for diclofop-methyl or 1.57 with fenoxaprop-p-ethyl when soil water deficit was maintained throughout the experiment. In contrast, treatment with tralkoxydim in wet conditions resulted in an ED_{50} of 0.332 compared with 0.495 under dry conditions. Clodinafop was less effective on wild oats at equivalent recommended rates than the three above mentioned herbicides, although its activity also decreased with soil water deficit.

The influence of soil water deficit, either before or after herbicide application, caused herbicide dose-responses for diclofop-methyl and fenoxaprop-p-ethyl in wild oat that were intermediate between those for the prolonged dry or wet treatments.

Table 2. The estimated dose of herbicide (as a proportion of the recommended rate) required to reduce survival of wild oat by 50% (ED_{50}). SE is the standard error for each ED_{50}.

Herbicide	Soil moisture content	ED_{50}	SE
Diclofop-methyl	wet	0.529	0.049
	wet/dry	1.369	0.134
	dry	3.767	0.623
	dry/wet	1.519	0.153
Fenoxaprop-p-ethyl	wet	0.585	0.044
	wet/dry	0.744	0.056
	dry	1.572	0.127
	dry/wet	1.226	0.095
Tralkoxydim	wet	0.332	0.026
	wet/dry	0.376	0.029
	dry	0.495	0.038
	dry/wet	0.342	0.027
Clodinafop	wet	1.272	0.082
	wet/dry	1.66	0.110
	dry	2.018	0.141
	dry/wet	2.162	0.158

Glasshouse experiment: annual ryegrass

Leaf yellowing occurred a week after application of all herbicide treatments in descending order of severity at equivalent rates: diclofop-methyl > clodinafop > tralkoxydim. Symptoms were less in the two treatments which were dry before application than in the two that were wet.

The dose-responses fitted for each herbicide are in Figure 2. The shape parameters (± SE) were 1.750 (0.204) for diclofop-methyl, 2.236 (0.184) for tralkoxydim, and 1.780 (0.143) for clodinafop. The ED_{50} values are in Table 3.

Diclofop-methyl gave more effective control of annual ryegrass than tralkoxydim or clodinafop at equivalent rates. The ED_{50} of diclofop-methyl was 0.146 in the wet treatment compared with 0.496 for tralkoxydim and 0.390 for clodinafop. The continuously dry treatment, and to a lesser extent the wet/dry treatment, resulted in greater survival of annual ryegrass than the continuously wet treatment. The ED_{50} of diclofop-methyl was 0.4 in the dry treatment, compared with 0.7 for tralkoxydim or clodinafop.

Table 3. The estimated dose of herbicide (as a proportion of the recommended rate) required to reduce survival of annual ryegrass by 50% (ED_{50}). SE is the standard error for each ED_{50}.

Herbicide	Soil moisture content	ED_{50}	SE
Diclofop-methyl	Wet	0.146	0.023
	Wet/dry	0.259	0.027
	Dry	0.405	0 .037
	Dry/wet	0.185	0.024
Tralkoxydim	Wet	0.496	0.038
	Wet/dry	0.551	0.042
	Dry	0 .745	0.057
	Dry/wet	0.386	0.030
Clodinafop	Wet	0.390	0.035
	Wet/dry	0.502	0.044
	Dry	0.721	0.063
	Dry/wet	0.425	0.038

Field experiment: wild oat and wheat

Establishment of wheat was 160 plants m^{-2} and wild oat was 183 plants m^{-2}. At the time of herbicide application, there was 73% ASM in the wet treatments (averaged to a soil depth of 0.5 m), compared with 25–38% in the dry treatments. The relative leaf water content of wild oat was 95% in the wet treatments and 88% in the dry treatments but these were not significantly different. Two weeks after application, there was 70% ASM in the wet treatments, 50% ASM in the wet/dry treatment, 15% ASM in the dry treatment, and 45% in the dry/wet treatment.

Leaf yellowing was observed on the wild oat from both diclofop-methyl and tralkoxydim within five days of application, but symptoms were most pronounced in the treatments wet before application. By the end of tillering of wheat, wild oat was completely killed by both diclofop-methyl and tralkoxydim in all the soil moisture treatments. At anthesis, DM of wild oat in the unsprayed controls was not significantly affected ($P > 0.05$) by soil moisture and the mean value of the four unsprayed treatments was 570 g m^{-2}.

Two weeks after application, symptoms of injury were observed in wheat similar to those seen in wild oat. The symptoms were in all treatments but were most severe in the diclofop-methyl × wet treatments. Wheat DM and tiller number m^{-2} were influenced by a significant interaction ($P < 0.05$) between soil moisture and herbicide treatment (Figure 3). Treatment with diclofop-methyl or tralkoxydim resulted in more wheat DM than in the unsprayed controls when the soil was wet throughout the experiment, and also in the wet/dry and dry/wet treatments (Figure 3a). However, when the soil was dry both before and after herbicide application there was little difference in DM between the unsprayed control and the herbicide treatments. Wheat tiller number showed a similar response (Figure 3b). Wheat tended to be shorter in the herbicide treatments, especially in the dry treatments, than in the unsprayed controls, but height was not significantly affected ($P > 0.05$) by herbicide or soil moisture treatment.

Discussion

The results of the glasshouse experiments clearly indicate that prolonged duration of soil water deficit reduce the dose-response of foliar-applied herbicides for both wild oat and annual ryegrass. This is in general agreement with reports that absorption, translocation and metabolism of foliar herbicides are reduced more in dry soils than under conditions of optimal soil moisture (Caseley 1987, Devine 1988, Wanamarter and Penner 1989). This response was similar for the three herbicides tested on annual ryegrass. In

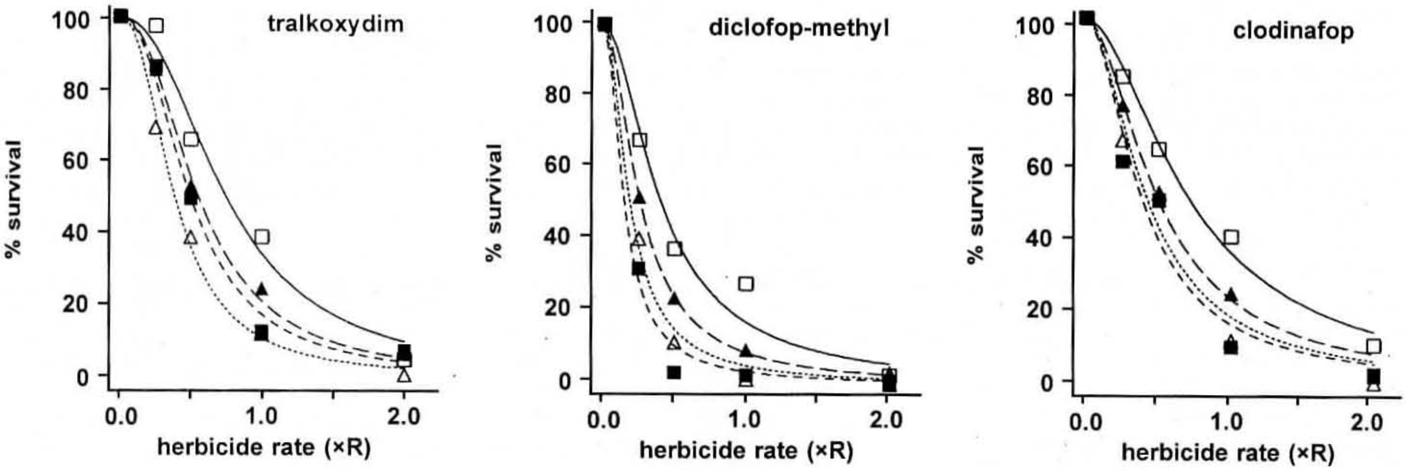

Figure 2. Response (% survival) of annual ryegrass to foliar-applied herbicides under 4 soil moisture treatments:
i. 'wet' ■, maintained close to 100% ASM until harvest at the end of tillering,
ii. 'dry' □, maintained close to 50% ASM until harvest,
iii. 'dry/wet' △, dry until herbicide application at the 3-leaf stage of growth followed by wet until harvest, and
iv. 'wet/dry' ▲, wet until herbicide application followed by dry until harvest.

contrast, in wild oat the efficacy of diclofop-methyl and fenoxaprop-p-ethyl was less than that of tralkoxydim, especially under dry conditions, while flamprop-methyl and clodinafop were less effective under all conditions. Wilcox *et al.* (1987) also found that the activity of diclofop-methyl on wild oat was more affected by soil water deficit than that of flamprop-methyl, which agrees with the results presented here. Therefore, farmers are most likely to experience unreliable performance with reduced rates of diclofop-methyl or fenoxaprop-p-ethyl compared with tralkoxydim on wild oat, and with tralkoxydim or clodinafop compared with diclofop-methyl on annual ryegrass.

Dry conditions after application tended to reduce the performance of the three ryegrass herbicides, whereas dry conditions before application had less effect. These results agree with the findings of Kudsk and Kristensen (1992), who concluded that weeds exposed to soil water deficit can recover quickly after watering and respond to herbicides. In contrast, control of wild oat was not consistently affected by duration of dry conditions either before or after application. The reason for this is unclear and requires further investigation.

The complete kill of wild oat by the 1×R rate of both diclofop-methyl and tralkoxydim in the prolonged dry treatment in the field experiment was surprising given the high level of survival recorded in the glasshouse experiment, and the findings of Leys *et al.* (1988), where all herbicides were more effective in pot trials than in field experiments. It is possible that treatment of wild oat in the field trial with gibberellic acid to break dormancy and improve germination made the plants more susceptible to the wild oat herbicides. Furthermore, the significant increases in wheat DM in all soil moisture treatments, except for the prolonged dry treatment (Figure 3), are the result of the removal of wild oat competition.

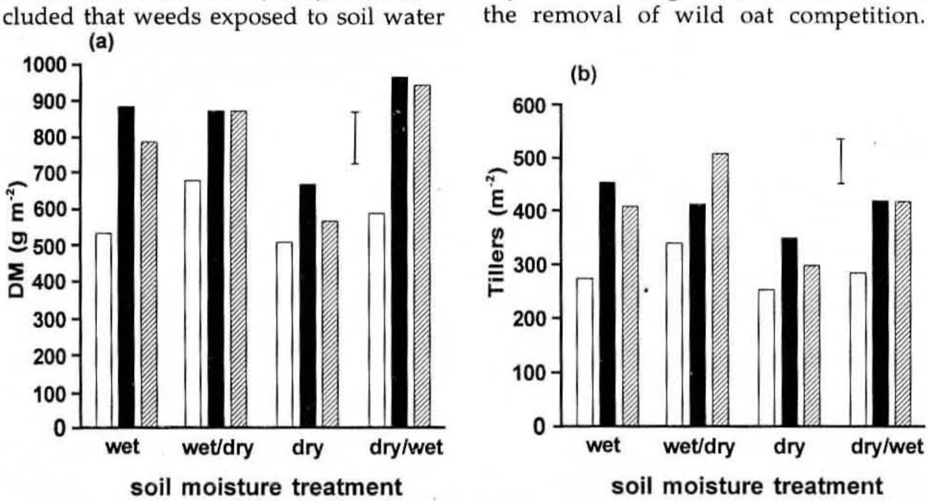

Figure 3. Response of (a) wheat dry matter and (b) tiller number to recommended rates of diclofop-methyl and tralkoxydim, under the 4 different soil moisture treatments. Vertical bars represent LSD (P <0.05).
▭ unsprayed control, ■ diclofop-methyl, ▨ tralkoxydim.

However, the reason for the reduced tolerance of wheat to both herbicides under prolonged dry conditions is unknown. Variations in soil moisture have already been implicated in altering the tolerance of wheat to wild oat herbicides in this environment (Lemerle *et al.* 1985). It is possible that reduced metabolism of the herbicide by the crop under low levels of soil moisture enhances crop phytotoxicity. Further studies on the impact of soil moisture and mechanisms responsible for variable wheat tolerance are needed to reduce the risk of yield loss to sensitive cultivars.

Generally, as is the case in this study, investigations of the influence of environmental factors on herbicide performance, examine the effect of altering levels of one factor under controlled conditions (Caseley 1987). However, these results are difficult to translate into farmer recommendations because natural conditions are not accurately reproduced and interactions of various factors are not usually examined.

Limited studies on the interaction of soil moisture with other factors on herbicide efficacy using climate simulators have been undertaken overseas to ensure more realistic results (Devine 1988, Kudsk and Kristensen 1992).

Measurements of the relative leaf water content of wild oat by the authors as a potential technique for farmers to monitor plant response to soil water deficit in relation to herbicide performance, showed little promise as a practical tool for farmers. Infra-red thermometry might be a more useful technique for this and needs to be evaluated.

The practical implication of this work is that farmers are more likely to experience unreliable control with some foliar-applied herbicides, especially at low rates of application and when conditions are dry.

Acknowledgments
The authors thank Mr. Bill Littlewood for technical assistance, Mr. Neil Coombes for statistical analyses and the Grains Research and Development Corporation of Australia for financial assistance. We also thank Drs. David Luckett and Phil Eberbach for criticism of the manuscript.

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