Chapter 7. Effect of late post-emergence selective herbicide treatment combinations on wild oat populations under continuous wheat cropping

7.1. *Introduction*

Wild oats have persisted in winter cropping areas despite the continuous input of herbicides. The annual application of the pre-emergence herbicide tri-allate fails to contain wild oat populations (Wilson *et al.* 1977; Fernandez-Quintanilla *et al.* 1987; Martin and Felton 1990). Likewise, many early post-emergence herbicides fail to contain wild oats, for example benzoylprop-ethyl (Breslin 1974; Jarvis and Clapp 1981) and barban (Wilson *et al.* 1977; Wilson and Phipps 1985). It is hypothesised that the lack of long term control under continuous wheat cropping despite the use of conventional herbicide strategies, is mainly a result of wild oat seed production from surviving plants (Peters *et al.* 1975; Medd 1992a) and partly a result of the low levels of seed dormancy (Chapter 1.2.7).

Some strategies resulting in substantial reductions of wild oat seed rain have resulted in substantial reductions in wild oat populations and/or seed banks in following years, particularly in Australia. For example, the tactics of rotating with summer crops (Wilson *et al.* 1977; Martin and Felton 1993) or long winter fallowing (Philpotts 1975) are effective methods of reducing wild oat seed rain by enabling the use of cultivation, atrazine or glyphosate in the fallow period to control plants effectively and halt seed production, thus producing dramatic declines in seed banks. There are no tactics used in Australia directly aimed at preventing wild oat seed production or seed rain within cereal crops.

The results from Chapter Five (Table 5.3) have shown that full RDRs of either fenoxaprop-p-ethyl or flamprop-M-methyl, without the addition of the adjuvants, resulted in reductions of seed production > 70%, if applied at the apparent optimum wild oat growth stage under favourable field conditions. At this level of efficacy, Medd and Pandey (1993) have assessed that such treatments should be economically feasible and contain wild oat populations over the long term.

7.2. *Aims*

The main objective of the work reported in this chapter was to test the prediction that large reductions in seed production, by annual late applications of flamprop, will contain wild oat populations and seed banks over a five year period, either when used alone or in combination with plant kill tactics such as pre- or early post-emergence herbicides. Thus a subsidiary objective was to test the hypothesis that in-crop seed production is the key to wild oat persistence. Wheat yields were measured to ascertain if any crop yield conservation benefits exist with the wild oat control strategies studied.

7.3. *Materials and methods*

A long term experiment (TAM92) was located at The Tamworth Centre for Crop Improvement (Lat. 31^{0}9'S, Long. 150^{0}59'E) on a red brown earth. A lucerne pasture for three years preceded the start of the experiment in 1992. Seed bank samples taken prior to establishment of the experiment detected only two wild oat seeds across the entire site (soil sampling methodology is described later).

Wild oat seeds consisting of 90% *A. ludoviciana* and 10% *A. fatua* (same seed source as experiment 92GH, Chapter Three) were hand broadcast along the central 2.5 m longitudinal section of each plot, except for the wild oat free plots, at an estimated density of 1,619 seed/m^2. The area not sown to wild oats represents the buffer zone. Plot dimensions were 4 m by 10 m with the last 1 m length of plot not sown to wild oats, representing another buffer zone. Seeds were incorporated into the soil by a single pass offset cultivation (uni-directional) and the action of a conventional seed drill.

The experimental design was a randomised complete block with seven treatments (Table 7.1) and four replications. Plot dimensions were 4 m by 11 m. Unless otherwise stated, agronomic details, herbicide application and measurement of weather conditions at the time of spraying wild oat herbicides were undertaken in accordance with methods described in Chapter 2.1.1, and analysed as described in Chapter 2.1.4 (details for experiment TAM92 are listed in Table 7.2).

Wireweed and annual ryegrass plant densities built up during the course of the experiment. Annual ryegrass was controlled by hand weeding and wireweed was controlled with a combination of hand weeding and applications of 2,4-DB at 1.6 kg a.i./ha (as Buticide® 2,4-DB herbicide - 2,4-DB 400 g/L) or chlorsulfuron at 15 g a.i./ha (as Glean® - chlorsulfuron 750 g/kg) when required. Wild oats were hand weeded regularly in buffer areas to prevent cross contamination of plots.

Table 7.1. Codes for the seven treatments used in experiment TAM92, with brief descriptions, including five wild oat control strategies using herbicides.

Treatment code	Description
WFC	Wild oat free control. No wild oat herbicides applied.
UTWC	Untreated wild oat control. No wild oat herbicides applied.
Pre only	Tri-allate applied at 840 g a.i./ha as the product Avadex®BW (tri-allate 400 g/L), applied pre-emergence to control wild oat plants.
Post only	Fenoxaprop-p-ethyl applied at 34.5 g a.i./ha as the product Puma®S (fenoxaprop-p-ethyl 69 g/L), applied early post-emergence to control wild oat plants.
SST only	Flamprop-M-methyl applied at 225 g a.i./ha as the product Mataven®L (flamprop-M-methyl 75 g/L), applied late post-emergence to minimise wild oat seed production. Flamprop-methyl at 450 g a.i./ha was used only in 1992, applied as Mataven®L (flamprop-methyl 100 g/L).
Pre + SST	A combination of Pre only and SST only treatments.
Post + SST	A combination of Post only and SST only treatments.

In each year after harvesting wheat, stubble was retained on the site, which was maintained free of weeds by chemical fallow using glyphosate at rates between 360 and 720 g a.i./ha (applied as Roundup® - glyphosate 360 g/L) when required. The stubble was cultivated with a single pass from offset discs just prior to sowing wheat with a conventional seed drill. Uni-directional single passes were made by the seed drill and offset discs so that passes were in the longitudinal direction of the plots.

After sowing wheat and spraying tri-allate, the herbicide was incorporated into the top 5 cm of soil by hand raking the soil perpendicular to the direction of the seed drill. Plant growth stages were recorded for both early and late post-emergence applications (Table 7.3).

Table 7.2. Agronomic and spraying conditions for applications of all wild oat herbicides in experiment TAM92.

	1992	1993	1994	1995	1996
Agronomic details:					
Date of sowing wheat	3.7.92	9.6.93	14.6.94	5.6.95	22.5.96
Wheat cultivar	Hartog	Hartog	Hartog	Hartog	Janz
Wheat sowing rate (kg/ha)	44	45	44	44	44
Time	2:15 pm	9:50 am	3:30 pm	3:00 pm	2:00 pm
Fertilisers (N:P:K kg/ha)	4.5:3.9:0.0[a] & 0.0:10.2:0.0[b]	6.8:5.9:0[a]	85.6:0.0:0.0[c] & 0.0:4.5:0.0[d]	85.6:0.0:0.0[c] & 0.0:4.5:0.0[d]	55.2:0.0:0.0[c] & 0.0:10.1:0.0[e]
Spraying conditions for tri-allate applications:					
Date of application	3.7.92	9.6.93	15.6.94	5.6.95	23.5.96
Time	11:50 am	2:30 pm	4:00 pm	10:30 am	9:20 am
Temp. Wet bulb (°C)	10.0	10.5	10.5	11.0	7.5
Temp. Dry bulb (°C)	17.0	14.0	16.5	15.0	9.0
Relative humidity (%)	41	65	48	63	81
Cloud cover (%)	50 (high)	95	Nil	10 (high)	15
Wind direction	NW	NW	W/SW	W	E/SE
Wind speed (m/s)	Light-Mod.	0.8 to 2.1	1.4 to 2.2	1.1 to 2.1	0.4 to 1.2
Average wind speed (m/s)	Light	1.8	1.8	1.6	0.8
Growing conditions	N/A	N/A	N/A	N/A	N/A
Spraying conditions for fenoxaprop-p-ethyl applications:					
Date of application	14.8.92	9.8.93	20.7.94	10.7.95	1.7.96
Time	4:30 pm	5:00 pm	4:50 pm	2:00 pm	3:00 pm
Temp. Wet bulb (°C)	10.0	10.5	9.0	10.0	9.5
Temp. Dry bulb (°C)	15.0	13.5	13.5	16.5	12.0
Relative humidity (%)	54	71	55	44	74
Cloud cover (%)	65	Nil	Nil	15	100
Wind direction	NW/W	Nil	SW	N/W	W/SW
Wind speed (m/s)	Light-Mod.	Nil	0.7 to 1.1	2.0 to 4.1	0.0 to 0.5
Average wind speed (m/s)	Light	Nil	0.9	3.4	0.1
Growing conditions	Excellent, growing actively	Excellent, growing actively	Good, growing actively	Good, growing actively	Good, growing actively
Spraying conditions for flamprop applications:					
Date of application	30.9.92	30.8.93	15.9.94	15.9.95	17.9.96
Time	12:40 pm	3:10 pm	1:00 pm	1:00 pm	12:00 pm
Temp. Wet bulb (°C)	10.5	15.0	11.5	16.5	17.5
Temp. Dry bulb (°C)	15.5	20.0	22.0	23.0	27.5
Relative humidity (%)	54	58	24	50	34
Cloud cover (%)	35	80	Nil	20	Nil
Wind direction	S/W	W	SW	N/W	NW
Wind speed (m/s)	1.4 to 3.5	0.6 to 0.9	0.5 to 1.6	1.9 to 3.9	1.5 to 4.5
Average wind speed (m/s)	2.8	0.8	0.8	2.3	2.7
Growing conditions	Excellent, growing actively	Excellent, growing actively	Fair to poor, early signs of moisture stress	Good, growing actively	Good, growing actively

[a] Starter 15 (N:P:K = 15:13:0).

[b] Double super phosphate (N:P:K = 0:17:0).

[c] Urea (N:P:K = 46:0:0).

[d] Single super phosphate (N:P:K = 0:9:0).

[e] Molybdenum single super phosphate (N:P:K = 0:9:0 with 0.02% molybdenum).

Table 7.3. Wheat and wild oat growth stages for early and late post-emergence applications of wild oat herbicides, along with spraying details (nozzle size and herbicide spray volume) of all herbicide treatments within experiment TAM92.

	1992			1993			1994			1995			1996		
Details of tri-allate applications:															
Teejet® flat fan nozzle size	8002			8002			8002			8002			8001		
Herbicide spray volume (L/ha)	133			113			129			136			121		
Details of fenoxaprop-p-ethyl applications:															
Teejet® flat fan nozzle size	8002			80015			8002			8002			8001		
Herbicide spray volume (L/ha)	133			117			129			136			98		
Wild oat growth stages[a] (averaged for all treatments involving fenoxaprop-p-ethyl):															
Zadoks DC for main stem only	10 to 13			12 to 30			7 to 13			10 to 12			10 to 13		
Vegetative (%)	100			99			100			100			100		
Elongating (%)	0			1			0			0			0		
Wheat growth stages[a] (averaged for all treatments involving fenoxaprop-p-ethyl):															
Zadoks DC for main stem only	11 to 14			12 to 31			12 to 13			11 to 13			12 to 15		
Vegetative (%)	100			99			100			100			100		
Elongating (%)	0			1			0			0			0		
Details of flamprop applications:															
Teejet® flat fan nozzle size	8002			80015			8002			8001			110015		
Herbicide spray volume (L/ha)	133			117			129			121			129		
Wild oat growth stages[a]:															
Zadoks DC for main stem only	11 to 53			13 to 33			13 to 51			13 to 47			14 to 32		
	P[b]	E[c]	S[d]	P[b]	E[c]	S[d]	P[b]	E[c]	S[d]	P[b]	E[c]	S[d]	P[b]	E[c]	S[d]
Vegetative (%)	36	46	42	72	100	78	71	63	69	74	74	74	64	64	64
Elongating (%)	62	48	52	28	0	22	25	28	26	16	16	16	36	36	36
Booting (%)	2	6	6	0	0	0	4	9	5	10	10	10	0	0	0
Wheat growth stages[a] (averaged for all treatments involving flamprop):															
Zadoks DC for main stem only	31 to 41			31 to 32			14 to 43			31 to 45			32 to 33		
Vegetative (%)	23			21			33			56			5		
Elongating (%)	77			79			67			36			95		
Booting (%)	0			0			0			8			0		

[a] See Chapter 2.1.1 for method of determining growth stages.
[b] Applies to Pre + SST treatments.
[c] Applies to Post + SST treatments.
[d] Applies to SST only treatments.

Four plastic segmented quadrats, each an area of 0.236 m^2, were pegged onto the soil spaced evenly along the central two metre longitudinal section of each plot where they remained until harvest. Wild oat plant densities and seed production were measured on all plants within the quadrats. Seed indexing was measured in all years to assist in the estimation of seed production (Chapter 2.1.2). A small plot header was used to harvest a strip of wheat no greater than 2.5 metres wide from within the central longitudinal zone of each plot, but not the buffer zones.

Soil samples, to measure wild oat seed banks, were collected after harvest each year. Fifty cylindrical soil core samples (7.5 cm diameter by 10 cm deep) were taken from each plot, consisting of two rows of 25 samples stratified along the plot. The soil core samples were wet sieved and the wild oat seed extracted using flotation and winnowing prior to counting (Medd 1992b). Dates for post-spraying measurements and harvest area of wheat are listed in Table 7.4. Statistical analyses were undertaken as described in Chapter 2.1.4.

Table 7.4. Experiment TAM92: Dates of post spraying measurements and area assigned for mechanically harvested wheat.

	1992	1993	1994	1995	1996
Harvesting details:					
Date of harvesting	22.12.92	1.12.93	2.12.94	5.12.95	10.12.96
Area harvested per plot (m^2)	14.25	12.00	24.38	14.25	16.93
Other dates of post spraying measurements:					
Seed indexing	1.12.92	3.11.93	17.10.94 & 2.11.94	11.9.95	1.10.96
Wild oat plant densities and seed production	22.12.92	30.11.93 & 1.12.93	1.12.94	30.11.95 & 4.12.95	21.11.96, 28.11.96 & 10.12.96
Soil sampling	25.2.93	1.12.93 & 2.12.93	6.12.94	15.12.95	17.12.96

7.4. *Results*

Wild oat seed production from the UTWC treatment ranged from 3,394 to 25,824 seeds/m^2 over a five year period (Table 7.5). Repeated annual applications of tri-allate (Pre only treatments) resulted in seed production of between 1,407 and 5,166 seeds/m^2, over the same period. In years 1993 and 1995, seed production from the Pre only treatment was not significantly different ($P>0.05$) to the UTWC treatment. All other treatments significantly reduced ($P<0.05$) seed production compared with the UTWC, over the duration of the experiment. Treatments containing late applications of flamprop kept seed production below 200 seeds/m^2 from years 1993 to 1996. The lowest seed production in any year was from either the Pre + SST or Post + SST treatments. Assuming potential seed production of all weedy treatments in 1992 was 7,430 seeds/m^2 (UTWC seed production), the reductions in seed production in 1996 for all herbicide treatments relative to the potential seed production in 1992 were, 75.8 (Pre only), 93.7 (Post only), 97.4 (SST only) and almost 100% (Post + SST and Pre + SST).

The levels of seed in the seed bank (Table 7.6) followed a similar trend to the seed production data (Table 7.5). After five years of repeated annual use of treatments, the UTWC increased the wild oat seed bank by 701% and the Pre only treatment by 148% compared with the initial level of 1,619 seeds/m^2. At the completion of the experiment, Post only, SST only, Pre + SST and Post + SST treatments reduced the initial wild oat seed bank by 23.7, 98.9, 99.6 and almost 100%, respectively, compared with the initial seed bank levels.

Wild oat densities did not change greatly in the five year period for UTWC, Pre only and Post only treatments (Table 7.7), whereas SST only, Post + SST and Pre + SST treatments reduced plant densities by 99.4, 99.7 and almost 100%, respectively, compared with the respective densities recorded in 1992.

Apart from 1992, wheat yields of SST only treatments were comparable with yields of Post only treatments because the average yield rankings were 4.0 and 4.2, respectively (Table 7.8). The UTWC treatment was consistently ranked the lowest in terms of wheat yield, followed closely by the Pre only treatment. The wheat yields from Post + SST and Pre + SST treatments were equivalent to WFC yields over all years, except for the Post + SST in 1994.

Table 7.5. Experiment TAM92: Wild oat seed production (seeds/m^2) following various wild oat control tactics over five years. Transformed data are presented in parentheses. The weed free control treatment was not included in the analyses.

	1992[a]	1993[b]	1994[a]	1995[b]	1996[a]
Treatment code:					
UTWC	7430	8777	5314	3394	25824
	(86.20)	(9.08)	(72.90)	(8.13)	(160.70)
Pre only	2107	5166	3994	1407	1798
	(45.90)	(8.55)	(63.20)	(7.25)	(42.40)
Post only	778	3.2	655	522	467
	(27.89)	(1.43)	(25.59)	(6.26)	(21.61)
SST only	2746	17	164	17	196
	(52.40)	(2.89)	(12.81)	(2.89)	(14.00)
Pre + SST	778	1.0	61	0.6	1.7
	(27.89)	(0.69)	(7.81)	(0.47)	(1.30)
Post + SST	132	4.3	17	13	4.8
	(11.49)	(1.67)	(4.12)	(2.64)	(2.19)
s.e.d.	(4.76)	(0.95)	(4.27)	(0.82)	(4.53)
Significance	P<0.001	P<0.001	P<0.001	P<0.001	P<0.001

[a] Data were square root transformed.
[b] Data were logarithmic transformed.

Table 7.6. Experiment TAM92: Wild oat seed bank (seed/m^2) following various wild oat control tactics, over five years. Transformed data are presented in parentheses. The weed free control treatment was not included in the analyses.

	1992[a]	1993[a]	1994[a]	1995[b]	1996[b]
Treatment code:					
UTWC	7150	10617	3564	5942	12964
	(84.56)	(103.04)	(59.70)	(8.69)	(9.47)
Pre only	1282	4255	2693	888	4023
	(35.81)	(65.23)	(51.89)	(6.79)	(8.30)
Post only	405	224	586	572	1236
	(20.12)	(14.96)	(24.21)	(6.35)	(7.12)
SST only	608	160	76	93	18
	(24.65)	(12.63)	(8.72)	(4.54)	(2.92)
Pre + SST	248	82	28	2.7	7.0
	(17.75)	(9.08)	(5.29)	(1.32)	(2.08)
Post + SST	161	89	64	9.0	0.3
	(12.69)	(9.44)	(8.00)	(2.30)	(0.25)
s.e.d.	(3.35)	(2.95)	(3.64)	(0.67)	(0.90)
Significance	P<0.001	P<0.001	P<0.001	P<0.001	P<0.001

[a] Data were square root transformed.
[b] Data were logarithmic transformed.

Table 7.7. Experiment TAM92: Wild oat plant density (plants/m^2) following various wild oat control tactics over five years. Transformed data are presented in parentheses. The weed free control treatment was not included in the analyses.

	1992[a]	1993[a]	1994[a]	1995[a]	1996[b]
Treatment code:					
UTWC	665	411	556	256	825
	(6.50)	(6.02)	(6.34)	(5.55)	(28.72)
Pre only	201	57	244	61	189
	(5.31)	(4.06)	(5.50)	(4.12)	(13.75)
Post only	126	1.0	33	32	87
	(4.85)	(0.70)	(3.53)	(3.48)	(1.98)
SST only	662	1.9	12	1.3	3.9
	(6.50)	(1.05)	(2.54)	(0.82)	(1.98)
Pre + SST	233	0.2	4.3	0.2	0.1
	(5.46)	(0.18)	(1.66)	(0.18)	(0.26)
Post + SST	118	0.6	2.9	2.6	0.4
	(4.78)	(0.46)	(1.36)	(1.27)	(0.63)
s.e.d.	(0.10)	(0.38)	(0.43)	(0.38)	(1.28)
Significance	P<0.001	P<0.001	P<0.001	P<0.001	P<0.001

[a] Data were logarithmic transformed.
[b] Data were square root transformed.

Table 7.8. Experiment TAM92: Wheat yield (t/ha) following various wild oat control tactics over five years. Numbers in parentheses represent the ranking of yield, (1) represents the highest and (7) the lowest yield in each year.

	1992	1993	1994	1995	1996
Treatment code:					
WFC	2.763 (1)	3.783 (1)	0.921 (1)	2.384 (4)	3.358 (2)
UTWC	0.977 (7)	0.559 (7)	0.147 (7)	1.496 (7)	0.494 (7)
Pre only	2.492 (4)	2.041 (6)	0.293 (6)	2.208 (6)	1.172 (6)
Post only	2.708 (2)	3.155 (4)	0.699 (4)	2.242 (5)	2.197 (5)
SST only	1.064 (6)	2.599 (5)	0.727 (3)	2.440 (3)	2.640 (4)
Pre + SST	2.422 (5)	3.736 (2)	0.839 (2)	2.789 (1)	3.423 (1)
Post + SST	2.553 (3)	3.255 (3)	0.645 (5)	2.490 (2)	3.188 (3)
s.e.d.	0.179	0.264	0.092	0.218	0.277
Significance	P<0.001	P<0.001	P<0.001	P<0.001	P<0.001

7.5. *Discussion*

The results of experiment TAM92 supports the predictions that the adoption of a strategy which leads to substantial reductions in wild oat seed production will result in great reductions of wild oat seed banks and populations over time. Therefore, the hypothesis that in-crop wild oat seed production is the main key to the persistence of the weed can be accepted. Without some level of seed dormancy, however, the entire population could be eliminated with one thoroughly successful application of herbicide. This finding agrees with the findings from the Australian literature (Medd and Ridings 1989; Madin *et al.* 1993; Mansooji 1993; Matthews *et al.* 1994; Medd and Dowling 1996) reviewed in Chapter 1.2.8. No literature could be found that suggests wild oat seed dormancy is the major mechanism for persistence in Australia, therefore wild oat management strategies that incorporate the prevention of seed production and/or result in large reductions of seed rain should reduce populations over time.

Large reductions in wild oat seed banks and populations occurred with the SST only treatment, resulting from large reductions in seed production. An estimation of the reduction in seed production was 89.5%, a value obtained from the first year, when SST only and UTWC treatments had no treatment difference prior to application of flamprop (Table 7.5). The reduction in seed production was excellent despite the applications being made at a reasonably late wild oat growth stage, which corresponded to 52% tillers elongating and 6% in boot (Table 7.3). Despite the lack of optimal application timing, the wild oat seed bank from the SST only treatment had declined by 90.1% after two years. This result agrees closely with the findings of Martin and Felton (1993), they recorded a 93% reduction in the wild oat seed bank under a sorghum rotation after two years. It is also likely that reductions in seed production from 'SST' treatments were not maximised because synergistic adjuvants such as Uptake® (Chapter Five) were not applied.

If a strategy which solely reduced seed production (SST only) was combined with either a plant kill tactic such as applications of early post-emergence (Post only) or pre-emergence (Pre only) herbicides, an economic benefit from crop yield conservation is likely to occur, combined with a greater reduction of the seed bank. However, single late applications of flamprop (SST only) resulted in lower wild oat seed banks and populations compared with

Post and Pre only treatments. An additional benefit of the SST only treatment over the Pre only treatment was better crop yield conservation in most years. Although Medd and Pandey (1993) have indicated that reductions in wild oat seed production of over 70% compared with conventional herbicide use were economically justified and would contain wild oat populations, this study has shown clearly that late applications of flamprop *per se* can reduce populations with a likelihood of returning a delayed economic benefit by conserving crop yield in the following year. The addition of a plant kill strategy in dense wild oat populations could thus be justified because of the immediate benefits of crop yield conservation.

This study also re-affirmed the inability of conventional herbicide tactics (Pre and Post only treatments) to reduce or contain wild oat populations over time. The variability of these treatments in reducing wild oat seed banks and populations is in agreement with the conclusion made by Martin and Felton (1993) for the repeated annual use of tri-allate.

Chapter 8. Integrating discussion

The results from experiments reported within this thesis have demonstrated a technique that consistently and substantially reduces wild oat seed production in wheat using both fenoxaprop-p-ethyl and flamprop (as flamprop-methyl or flamprop-M-methyl). Specific conclusions have been drawn in the relevant experimental chapters regarding time of application, herbicide dose rate, addition of adjuvants, crop safety and the long term reduction of wild oat populations / seed banks. Therefore, this discussion will concentrate on the aspects in relating to the practical application of the results. The findings have considerable commercial potential because they, for the first time, offer growers a method of directly controlling seed production of a weed in a crop grown for grain, and thus potentially provides a new tool for wild oat management. Based on the earlier pilot studies reported by Medd *et al.* (1992), the term 'selective spray-topping' was suggested to describe the technique of late post-emergence application of selective herbicides in a crop to reduce weed seed production. This is considered an appropriate terminology because it distinguishes the method from the early use of pre or post-emergence herbicides which aim to minimise competition from weeds to conserve crop yield, and from other spray-topping methods as discussed below in Chapter 8.5.

In order for the findings to be commercialised, many practical matters need to be considered. Such matters include, the limits of wild oat application developmental stages ('timing window') at which reductions in seed production are acceptable but unlikely to be optimal, the minimum dose rates that can be used effectively and the factors that affect rates, the safety of various treatments with respect to wheat crops, the economics of some effective treatments, the management of herbicide resistance and the role of the findings in the management of wild oats.

8.1. *'Timing window'*

As outlined in Chapter 1.3.2, the recruitment of wild oat seedlings occurs over a protracted period from autumn to spring, with the main flushes generally occurring early in the life of a winter crop. It was also concluded from a review of literature that seed production from escapes, survivors or new recruits which emerge after in-crop control treatments are undertaken are the likely cause of wild oats persistence. The work reported in Chapter Seven confirms that if seed production is reduced, wild oat populations are depleted dramatically. From a practical perspective, the application of herbicides which aim to reduce seed production should therefore be delayed until recruitment is completed to ensure that all plants with a potential to reproduce are targeted. However, the results from experiments reported in Chapters Three and Four determined that there is an apparent optimum wild oat growth stage of 20% tillers elongating (approximately Zadoks DC = 31 to 32) when herbicides should be applied to achieve maximum efficacy. Unless these two conditions coincide in time, the result may be less than optimal. Consequently, application of herbicides at the apparent optimum developmental stage is a compromise between minimising seed production of the earlier cohorts (larger plants) and the ability to affect late emerging wild oats.

Although applications of fenoxaprop-p-ethyl or flamprop at the apparent optimum time of application are likely to result in minimum wild oat seed production, earlier or later applications may also achieve acceptable results, ensuring a wider application 'timing window'. A wider application window should allow additional time for farmers or contractors to treat wild oat infested paddocks in the event of delays because of inclement weather, labour shortages or machinery breakdown. Reductions in seed production for post-optimal applications in field experiment IN92RXT include 89 and 88% reductions with fenoxaprop-p-ethyl and flamprop-methyl respectively (mean of half and full RDRs), after application to wild oats in the boot stage (4% tillers in boot and 1% with panicle emergence) (Chapter 4.4.1). Likewise, half RDRs at the same time of application, regardless of herbicide applied, resulted in a 79% reduction in seed production whereas the value was 94% for full RDRs (Chapter 4.4.1). These trends were also apparent in experiment CR92RXT at a similar wild oat developmental stage (13% tillers in boot and 3% with panicle emergence) (Chapter 4.4.2). Therefore it is likely that post-optimal applications, up to wild oats in the late boot stage, with environmental and crop conditions similar to experiments IN92RXT and CR92RXT, will result in acceptable reductions in wild oat seed production. However, in relatively low density and/or uncompetitive crops (experiments IN93RXT and SM94RXT) and/or under moisture stressed conditions (experiment SM94RXT) herbicide efficacy was reduced. This was apparent since reductions in seed production for fenoxaprop-p-ethyl and flamprop-M-methyl, averaged for half and full RDRs, were 56 and 77% respectively after applications to wild oat in the early boot stage (4% tillers in boot and 28% elongating) in experiment SM94RXT (Chapter 4.4.4). Based on these findings, flamprop-M-methyl would be preferred over fenoxaprop-p-ethyl under unfavourable conditions and post-optimal times of application as it appears to be more effective and reliable.

In summary, the length of the 'timing window' starts when wild oats are just commencing jointing (Zadoks DC = 31 or after the first node is detected) and finishes during the mid-booting stage (Zadoks DC = 45, approximately 5 to 10% tillers in boot stage). Likewise, the start and finish of the 'timing window' for wheat growth stages are approximately similar to those of wild oats since the average growth stages of each species were shown to be closely correlated (Chapter 6.4.5). The duration of this 'timing window' estimated from field experiments would be between 20 and 30 days.

Completion of early post-emergence control of wild oats in northern NSW occurs from May to early August, depending on sowing dates, available soil moisture and location within the northern grain region. This generally corresponds to the coolest time of the year. Critical times for late post-emergence applications of herbicides are likely to occur in late August to early October, when temperatures are warmer, there is less chance of frosts and when wild oats have faster growth rates. Therefore, there is less likelihood of herbicide failure due to frost stress or inactively growing plants for late post-emergence applications of flamprop-M-methyl or fenoxaprop-p-ethyl, providing moisture is not the limiting factor. Label recommendations also suggest that better results are obtained when wild oats are actively growing.

8.2. *Dose rate and adjuvants*

Applications of half RDRs within the 'timing window' under conditions similar to those experienced in 1992 and 1993 experiments resulted in acceptable reductions in wild oat seed production, as discussed previously in the 'timing window' sub-section. Nevertheless, under less favourable conditions such as when crops are lacking vigour due to poor fertiliser management or drought, low crop densities or the choice of uncompetitive cultivars, the application half RDRs may result in unacceptable herbicide efficacy, particularly if timing is post-optimal. This was confirmed after applications of half and full RDRs of either herbicide, to wild oats at the late jointing stage (30% tillers elongating) in experiment IN93RXT (considered to have a poorly competitive wheat crop), resulted in 53 and 88% reductions in seed production relative to the untreated plants, respectively (Chapter 4.4.3). Therefore the application of full RDRs would be more acceptable under such conditions. The extremely dry conditions experienced in experiment SM94RXT (Chapter Four) were the likely cause of the unacceptable reductions in wild oat seed production for most treatment combinations. Despite this, flamprop-M-methyl reduced seed production sufficiently (77% relative to the untreated) after application to wild oats at the early boot stage (4% tillers in boot), averaged for half and full RDRs. Wilcox *et al.* (1987) also concluded that flamprop-methyl was less affected by drought than other herbicides (such as diclofop-methyl). Under these circumstances it would be logical to opt for full RDRs of flamprop-M-methyl to ensure that herbicide efficacy is maintained.

It was shown in experiment IN92RXT that half RDRs applied near the apparent optimum time resulted in similar reductions in wild oat seed production compared with full RDRs made at the end of the 'timing window' (Chapter 4.4.1). This effect was similar in experiment CR92RXT for the same times of application and herbicide rates (Chapter 4.4.2). Furthermore, half RDRs applied at the commencement of the 'timing window', resulted in significantly less ($P<0.01$) wild oat seed production than full RDRs applied at the end of the 'timing window' (Chapter 4.4.2). Therefore, substantial cost savings would result if applications were made early in the 'timing window' near or just prior to the apparent optimum wild oat growth stage, since half RDRs would suffice. However, rate cutting is not advisable when crop or environmental conditions are unfavourable or when applications are made late in the 'timing window'. Consequently, to minimise cost, applications of herbicide should be made as close as possible to the apparent optimum time of application or slightly earlier to avoid rapid declines in herbicide efficacy at the end of the 'timing window'.

As Medd and Pandey (1991) have stated with regard to the use of herbicides in New South Wales, recommended rates listed on herbicide labels are contracts, therefore farmers and spray contractors are legally required to apply herbicides at the rate listed. Generally product labels state one herbicide rate for a particular situation, giving no flexibility. With this in mind, and from the results within Chapters Four and Five, it would be logical to strive for a label recommendation that incorporates a range of rates, between half and full RDRs. This would provide an opportunity to reduce herbicide inputs depending on the seasonal and crop conditions and to minimise the potential for herbicide residues in wheat plus give immediate cost saving to the farmer. Although not tested in these studies, residues in grain do not appear to be an issue when the herbicides are applied in the 'timing window', as discussed in Chapters 8.3 and 6.5.

Results presented in Chapter 5.4.2 show that adjuvants may also enhance efficacy such that there is a synergy with herbicides applied at half RDRs. Of the six adjuvants tested initially, Uptake®, Pulse® and BS-1000® were frequently associated with improved herbicide efficacy. However, Uptake® was superior overall because of consistent improvements in efficacy, with reductions in seed production from half RDRs + Uptake® being comparable to full dose rates without adjuvants. The extent of this synergy was such that the addition of Uptake® reduced wild oat seed production by an additional 66.4% over and above herbicide application, averaged for quarter and half RDRs without adjuvants under conditions reported in experiment CR93ADJ (Chapter 5.3). The results also indicate that late post-emergence applications of herbicide with adjuvants are likely to have more robustness and reliability than similar herbicides without adjuvants under less than optimal conditions.

Wild oat seed production (total seeds/m^2) reported for field experiments aimed at investigating effects of time of application, herbicide dose rate and addition of adjuvants (Chapters Four and Five) over-estimates the potential input of viable seed to the seed bank because there was no accounting for effects on seed viability. There were indications from the pot experiment 92GH that late post-emergence applications of either fenoxaprop-p-ethyl or flamprop-methyl reduced seed viability after most times of application (Chapter 3.4.1).

Jensen (1990) has shown that seeds produced from *A. fatua* plants following late post-emergence treatment with an analogue of flamprop had lower weights compared with seeds from untreated plants and did not emerge in the field the following autumn and spring. Furthermore, research with seed from other weed species resulted in strong positive correlations between seed size and germinability, such that larger seeds have greater ability to germinate compared with smaller seeds (Schaal 1980; Hendrix 1984; Stanton 1984; Chandra Babu *et al.* 1990). Although seed size or weight was not measured in all pot (Chapter Three) and field experiments (Chapters Four and Five), it is likely that the significantly lower levels of viability, measured from pot experiments, for most application growth stages was partly due to reduced seed size. From other observations it was noted that regrowth of panicles late in the season was very small and most seed produced from these panicles appeared much smaller than untreated seed or was not filled. Therefore, research could be warranted to investigate wild oat seed weight and seedling vigour as well as viability of seeds produced in the field after applications of flamprop-M-methyl and fenoxaprop-p-ethyl.

8.3. *Crop safety*

There was no evidence to suggest that applications of fenoxaprop-p-ethyl and flamprop made within the 'timing window' in combination with wild oat competitive effects reduced yields or kernel weight of wheat, irrespective of other visual symptoms (Chapter Six). Most wheat cultivars were slightly shorter, by not more than 5% of the respective untreated wheat heights, but certain cultivars exhibited greater reductions in height after the application of full and twice RDRs of flamprop-M-methyl. The cultivars that exhibited noticeable height reductions were Yallaroi, Sunco, Meteor and Hartog. Leaf tip chlorosis, combined with leaf tip necrosis for more severe cases, was noted especially on the upper canopy leaves. Therefore applications of fenoxaprop-p-ethyl or flamprop-M-methyl within the 'timing window' at the rates suggested previously, are likely to be commercially acceptable on wheat cultivars tested in this work.

To ensure that growers have broad options, more research is required to investigate sensitivity, rate and time of application on all currently grown cultivars besides those tested for this thesis. Storrie *et al.* (1998) have suggested that the common link between cultivars that show sensitivity to flamprop-M-methyl is the occurrence of the Sr 26 gene for stem rust resistance. These cultivars should therefore be tested rigorously in any future crop tolerance research. Furthermore, such future research should investigate the effects of adjuvants, particularly Uptake® in combination with flamprop, since other reports have noted increased crop damage associated with adjuvants (Behrens 1964; Madin and Martin 1990; Murphy *et al.* 1995).

8.4. *Economics*

The average yield increase following late post-emergence applications of fenoxaprop-p-ethyl or flamprop was approximately 8% (Chapter Six). Assuming the average Australian wheat yield is 1.5 t/ha and the wheat quality is ASW (Australian Standard White), with a farm gate value of $120/t, the increase in wheat yield would return an extra $14.40/ha, which would greatly offset the cost of the herbicide (e.g. flamprop-M-methyl at half and full RDRs without adjuvants would cost $16.50 and $33.00/ha, respectively).

Besides the short term considerations, a long term economic impact of reducing wild oat seed production was evident in experiment TAM92 (Chapter Seven). There was a net yield increase of 61% (over five years) of wheat after annual applications of a pre-emergence herbicide (tri-allate) combined with late post-emergence applications of flamprop compared with annual applications of tri-allate alone. For this experiment, average annual yield conservation was 1.0 t/ha resulting in a return of $120/ha/annum (assuming ASW quality) which is almost four times the cost of herbicide if applied at full RDRs. Likewise, the benefit of combining annual early post-emergence plant kill tactics with late post-emergence applications of flamprop resulted in net yield increases of 10% compared with annual early post-emergence plant kill tactics. This yield conservation was equivalent to 0.23 t/ha/annum which would return an additional $27.60/ha/annum (assuming ASW quality). This would more than offset the cost of half RDRs but would not quite cover the cost of annual application at full RDR. Although yields of all four treatments mentioned above were not different in the first year after an initial wild oat seed bank of 1,619 seeds/m^2, the yield gains in the following years were therefore a consequence of reduced wild oat populations due to reductions in seed production and rapid declines of seed banks. It was therefore shown from this experiment that wild oat seed production was the key to its persistence because seed production and wild oat seed banks both followed similar downward trends over time. This is not to say that annual late post-emergence applications of flamprop used without other herbicides are uneconomical. Results from experiment TAM92 (Chapter Seven) also showed that the average wheat yield following annual late post-emergence applications of flamprop alone, over five years was 1.89 t/ha compared with 1.64 t/ha for annual pre-emergence applications of tri-allate alone. The difference between these treatments being 0.25 t/ha/annum equivalent to a return of \$30/ha/annum (assuming ASW quality) and significantly lower wild oat seed banks / populations than annual applications of tri-allate alone, after a five year period (Chapter 7.4).

Therefore, late post-emergence applications of flamprop-M-methyl in combination with either pre- or early post-emergence treatments (i.e. treatments investigated in the seed bank experiment (Chapter Seven)) are likely to return a financial benefit. It is likely that under low wild oat densities, annual late post-emergence applications of flamprop-M-methyl alone are economically feasible since they are capable of reducing wild oat seed banks with time and wheat yields were mostly conserved once wild oat densities had declined to low levels (Chapter 7.4).

Further cost savings could be obtained using adjuvants to improve herbicide efficacy. For the small cost of adding Uptake® (\$2.75/ha, assuming herbicide spray volumes are 100 L/ha) to flamprop-M-methyl, it is likely that RDRs may be reduced from full to half RDR without noticeable loss of efficacy (Chapter 5.4.2). This would represent a cost saving of \$13.75/ha.

Wilson and Cussans (1975) justified the up-front costs of controlling seed production by the benefits of reducing the wild oat populations. The justification is explained more precisely by Medd and Pandey (1993), in that addition to lower populations, reductions of herbicide inputs can be achieved if populations are low enough to warrant no herbicide application, especially for increasing the efficacy of herbicides and expected yield of wheat.

Weed management has largely been justified using the threshold concept to ensure benefits exceed costs in the short term. Economic optimum thresholds go some way towards accounting for long term effects as they are the weed densities that produce the best long term economic benefit (Cousens 1987; Jordan 1992) by considering short and long term costs. Jordan also noted that future costs are determined by seed production of uncontrolled weeds, requiring thresholds to be adjusted downwards as noted by Norris (1992). It would appear however, that simulation methods such as dynamic programming, which capture the long term states or population trends together with economic benefits, are more appropriate tools for evaluating weed control methods which aim to achieve population decline as distinct from purely evaluating benefits solely from yield conservation. This method simultaneously captures benefits from herbicide savings as well as yield benefits by optimising control inputs. For instance, Jones and Medd (1997) found that strategies which greatly reduced wild oat seed production combined with winter fallowing or conventional in-crop herbicide usage lead to greatly improved economic benefits, vindicating the approach of managing populations to reduce the seed bank.

8.5. *Role in wild oat management*

It is envisaged that the main benefit of late post-emergence applications of fenoxaprop-p-ethyl or flamprop-M-methyl would be as a long term management tool of wild oats. In deciding to use this new technique, growers should plan ahead in choosing the crop and cultivar to plant. At present, flamprop-M-methyl is registered only for use on feed and bread wheats. As noted on the flamprop-M-methyl product label, flamprop is not registered for durum wheats as they are especially sensitive. After planting and managing the crop for yield conservation, careful regular inspections of each paddock are required to ensure that weed / crop developmental stages are assessed correctly, along with consideration of the growing conditions. In situations where wild oats are not the dominant weed species, this new technique will not affect other weed species since flamprop-M-methyl has activity only against wild oats (Anon. 1990). Furthermore, it is suggested that this new technique not be used continuously over several seasons because over-reliance on any one herbicide chemical group may result in herbicide resistance (Maxwell and Mortimer 1994; Jasieniuk *et al.* 1996). Nonetheless, circumstances where late post-emergence applications of either fenoxaprop-p-ethyl or flamprop-M-methyl may be beneficial, include:

- Seasons with prolonged periods of drought or water logging in the early establishment phase of wheat, preventing the application of pre or early post-emergence herbicides. The 'timing window' could be of benefit if the season improves near the early jointing stage of the wild oats / wheat.
- Where there is substantial late recruitment.
- Where control has been less than adequate or has failed following pre or early post-emergence applications of wild oat herbicides.

- Where over-reliance of herbicides from Group A has resulted in herbicide resistance or the increased risk of achieving herbicide resistance. In these situations the use of flamprop-M-methyl is preferred, since it should have efficacy against Group A herbicide resistant biotypes of wild oats.
- In wheat with low wild oat densities. Situations where this is likely to occur include the first or second year in a continuous wheat rotation after a long fallow or following summer cropping or a pasture phase, or after normal pre or early post-emergence wild oat control and with the likelihood of late wild oat emergence.

The efficacy of fenoxaprop-p-ethyl or flamprop-M-methyl may be further improved despite applications made at the apparent optimum time and the addition of adjuvants. This could be achieved in the light of the information in Chapter 1.3 because achievable agronomic practices such as increasing the competitiveness of wheat and selecting the appropriate crop rotations to take advantage of possible allelopathic interactions, are likely to further reduce wild oat seed production.

Reductions in seed production (seeds/m^2) were mainly attributable to reductions in wild oat fecundity (seeds/plant), which in turn was generally affected by reductions in panicle seed set (seeds/panicle) and panicle production (panicles/plant) and occasionally by spikelet seed set (seeds/spikelet) (Chapters Three to Five). The relationship between these parameters is illustrated in Figure 2.2. Thus the main impact is due to a dual effect on reducing panicle formation as well as the size of panicles.

Applications of either flamprop-M-methyl or fenoxaprop-p-ethyl to *A. fatua* resulted in greater fecundity (seeds/plant) and seed viability than those of *A. ludoviciana* (Chapter 3.4.2) and consequently the continuous use of either flamprop-M-methyl or fenoxaprop-p-ethyl could possibly impose a selection pressure favouring *A. fatua* in mixed populations. However, no difference in efficacy was found between the herbicides on *A. fatua* (Chapter 3.4.2), thus selection of herbicide would be determined by other agronomic or economic benefits. In regions where *A. ludoviciana* dominates, such as the northern grain belt of New South Wales and Queensland, the use of flamprop-M-methyl would be preferable because it tended to be more effective and reliable than fenoxaprop-p-ethyl on *A. ludoviciana*.

Other spray-topping techniques which aim to reduce seed production have been widely adopted in Australia for pasture sanitation and salvage spraying in crops, and there are many similarities as well as differences from the technique developed in this thesis. Spray- or pasture-topping differs from the late application of selective herbicides termed 'selective spray-topping', because it involves the use of non-selective herbicides such as paraquat or glyphosate, and the optimum application growth stage is generally around anthesis or the early dough stage. Pasture-topping was developed to reduce annual grass seed production in pastures in order to deplete seed banks and disease inoculum prior to the cropping phase. Crop-topping on the other hand, which also involves the use of non-selective herbicides, is applicable in crops once they have reached physiological maturity and is of most relevance to crops such as pulses that are prone to weed invasion late in the season due their uncompetitive nature. These differences and distinctions in terminology are critical and must be understood clearly to prevent confusion. However, there are similarities between the techniques which include the use of low rates (sub-lethal or sub-recommended rates) of herbicides (Blowes *et al.* 1984) and that efficacy usually declines quickly outside the optimum 'timing window' (Blowes *et al.* 1984; Jones *et al.* 1984; Richardson *et al.* 1987; Dowling and Nicol 1993; Mayfield 1994).

The adoption of long fallowing or winter fallowing associated with crop rotations has provided excellent control of wild oat populations in Australia (Chapters 1.2.1 and 1.2.2, respectively), however this can involve land being unproductive and vulnerable to erosion in the fallowing period, and sometimes the forced necessity to rotate to alternative crops may not be as profitable. Apart from these techniques, the common in-crop technique for the control of wild oats undertaken in northern New South Wales in 1985 was the use of tri-allate (30% of people surveyed) and flamprop-methyl (5% of people surveyed) (Martin *et al.* 1988). The continuous use of these treatments and the practice of not treating low densities of wild oats ('non-yield threatening densities') are the probable causes of wild oat persistence via seed production (Chapter 1.2.8). Therefore, to successfully manage wild oats in wheat, a paradigm shift from the traditional emphasis on plant kill for yield conservation, to one of containment of populations by minimising seed production is reasonable. This would require efforts to change grower perceptions of managing the wild oat problem from one of treating annual infestation to that of managing populations over the longer term. This new technique of 'selective spray-topping' will allow farmers to better manage wild oat populations in situations that occur frequently, as mentioned previously (see point notes in: Role in wild oat management) by minimising wild oat populations of either herbicide resistant or susceptible plants. Since flamprop-M-methyl is a Group K herbicide and that most selective wild oat herbicides are in Group A, the use of flamprop-M-methyl has great potential for minimising the onset of Group A herbicide resistance in wild oats by using the practise of rotating to different herbicide groups regularly (Powles and Holtum 1990; Powles and Howat 1990; Jutsum and Bryan 1992) (Chapter 1.2.5).

As a conclusion, the broad objectives, as set out in Chapter 1.5, have been met by defining the apparent optimum time of application (in relation to wild oat development stage), identifying synergistic adjuvants, defining optimum herbicide dose rates under specific environmental conditions and ensuring that potential commercial treatments are not associated with unacceptable crop (wheat) damage. Moreover, the hypothesis that population control can be achieved by reducing seed production using late applications of selective herbicides has been found to be acceptable.

It is further concluded that the potential to directly manipulate (minimise) seed production using selective post-emergence herbicides, as shown in this work, could be extended to other weed species that have short-lived seed characteristics and low levels of dormancy.