Chapter 3. Pot studies: Determining optimum growth stage for late post-emergence applications of selective herbicides to wild oats

3.1. *Introduction*

Several studies have reported on the use of flamprop and fenoxaprop-p-ethyl for control of wild oat plants when applied at growth stages ranging between the two leaf and early jointing stages, i.e. Zadoks DC = 12 to 30 (Wilson 1979b; Kirkland and O'Sullivan 1984; Friesen 1987; Anderson *et al.* 1989; Anderson and Howat 1990; Hulme 1991). Very few studies have measured the effects of herbicides (Jeffcoat *et al.* 1977; Jensen 1990) on wild oat seed production, when applied after the early tillering stage. Although Medd *et al.* (1992) found that flamprop-methyl and fenoxaprop-p-ethyl gave excellent control of seed production, they did not study the effects of application at different growth stages. Consequently, there is clearly a gap in knowledge regarding the effects of application at different growth stages (especially between late tillering and the booting stage) on the efficacy of flamprop and fenoxaprop-p-ethyl for minimising seed production in wild oats.

3.2. *Aims*

The primary objective of the two studies reported in this chapter was to determine the optimum wild oat growth stage, for plants grown under controlled conditions when treated with flamprop (either as flamprop-methyl or flamprop-M-methyl - see Appendix Three for comparative efficacy data regarding formulations) or fenoxaprop-p-ethyl, in order to minimise seed production and seed viability. A subsidiary objective of the second experiment was to determine if the responses differed between the main species of wild oats, *A. ludoviciana* and *A. fatua*. Assessments were made on a range of reproductive parameters with the aim of identifying factors that might contribute significantly to any reduction in seed production.

3.3. *Materials and methods*

3.3.1. Investigating herbicide efficacy in relation to growth stage

Two pot experiments were conducted in or adjacent to a glasshouse at the Agricultural Research and Advisory Station Glen Innes (Lat. 29°42'S, Long. 151°42'E), using a randomised complete block design. The first experiment (92GH) investigated seven times of application for both flamprop-methyl and fenoxaprop-p-ethyl using half the recommended dose rates (RDRs) (Chapter Two) and an untreated control, replicated eight times. Seed used for this experiment consisted of a mixture of 90% *A. ludoviciana* and 10% *A. fatua* and was obtained from the Warialda (Lat. 29°33'S, Long. 150°34'E) district following the 1991 harvest. When planting, seeds were allocated randomly to pots irrespective of their primary, secondary or species status. *A. ludoviciana* seeds were forcibly separated prior to sowing.

The second experiment (94GH) tested responses to flamprop-M-methyl and fenoxaprop-p-ethyl at half RDRs for three times of application and the full RDRs (Chapter Two) at only the second time of application. These treatments were common to both *A. ludoviciana* and *A. fatua*, planted separately. The experimental design was a randomised complete block with nine replications. Seed of *A. fatua* was sourced from a railway right-of-way verge near Orange (Lat. 33°17'S, Long. 147°4'E) while the *A. ludoviciana* seed was separated from the same batch of seed used for 92GH. Only primary seeds of *A. ludoviciana* were planted to overcome the high levels of dormancy and achieve synchronised establishment.

Seeds in both experiments were sown into black plastic pots (15 cm diameter) filled with a sand / loam / peat mixture. Five seeds were sown per pot, at a depth of 3 to 5 cm and seedlings later thinned to one per pot. The most advanced or delayed seedlings were removed from the pots to unify growth stages among plants. Automatic watering systems applied approximately 2 mm of water twice a day, and this was increased to three times per day as wild oats grew larger. Other weed species where removed by hand when needed and fertilisers were applied occasionally to maintain plant health. The spraying conditions and growth stages for experiments 92GH and 94GH are outlined in Tables 3.1 and 3.2, respectively. Details of experimental maintenance and assessment are described in Table 3.3.

Table 3.1. Spraying conditions and plant growth stages for experiment 92GH.

Time of application	1	2	3	4	5	6	7
Spraying conditions:							
Date	27.9.92	2.10.92	6.10.92	13.10.92	19.10.92	26.10.92	30.10.92
Time	3:15 pm	11:00 am	5:00 pm	11:10 am	2:15 pm	2:30 pm	3:15 pm
Wet bulb (^{0}C)	10.0	10.5	13.0	11.0	10.0	13.0	15.0
Dry bulb (^{0}C)	17.0	18.0	18.5	15.0	15.0	21.0	20.0
Rel. humidity (%)	41	38	54	62	54	39	58
Cloud cover (%)	10	< 5	5	30	30	20	40
Wind speed (m/s)	0 to 1.5	0.2 to 0.9	0.6 to 1.2	0.8 to 3.0	0.3 to 1.4	0.9 to 3.0	0.8 to 2.6
Average (m/s)	0.4	0.6	1.0	1.5	0.7	1.8	1.5
Wild oat growth stages for fenoxaprop-p-ethyl treatments[a]:							
Zadoks DC for main stem only	13 to 14	14 to 15	14 to 15	15 to 37	32 to 41	33 to 49	37 to 55
Vegetative (%)	100	100	100	81	43	33	17
Elongating (%)	0	0	0	19	56	48	52
Booting (%)	0	0	0	0	1	19	26
Inflorescence (%)	0	0	0	0	0	0	5
Wild oat growth stages for flamprop-methyl treatments[a]:							
Zadoks DC for main stem only	13 to 14	14	14 to 31	31 to 32	32 to 41	41 to 49	45 to 53
Vegetative (%)	100	100	99	79	57	19	29
Elongating (%)	0	0	1	21	42	64	42
Booting (%)	0	0	0	0	1	17	26
Inflorescence (%)	0	0	0	0	0	0	3

[a] See Chapter 2.1.1 for method of determining growth stages.

Table 3.2. Spraying conditions and plant growth stages for experiment 94GH.

	A. fatua				*A. ludoviciana*			
Time of application	1	2	2[a]	3	1	2	2[a]	3
Spraying conditions:								
Date	14.10.94	21.10.94	21.10.94	26.10.94	14.10.94	21.10.94	21.10.94	26.10.94
Time	2:30 pm	11:15 am	11:15 am	4:10 pm	11.00 am	11:15 am	11:15 am	4:10 pm
Wet bulb (°C)	11.5	17.0	17.0	13.0	11.5	17.0	17.0	13.0
Dry bulb (°C)	19.0	25.0	25.0	23.0	19.0	25.0	25.0	23.0
Rel. humidity (%)	40	43	43	29	40	43	43	29
Cloud cover (%)	40	60	60	70 (high)	40	60	60	70 (high)
Wind speed (m/s)	1.0 to 2.4	2.8 to 5.4	2.8 to 5.4	0.0 to 2.0	1.0 to 2.4	2.8 to 5.4	2.8 to 5.4	0.0 to 2.0
Average (m/s)	1.6	3.9	3.9	0.7	1.6	3.9	3.9	0.7
Wild oat growth stages for fenoxaprop-p-ethyl treatments[b]:								
Zadoks DC for main stem only	13 to 31	31 to 43	31	31 to 45	14 to 31	31 to 41	31 to 43	31 to 45
Vegetative (%)	97	72	71	70	96	81	79	69.5
Elongating (%)	3	24	29	11	4	18	20	19.5
Booting (%)	0	4	0	19	0	1	1	11
Inflorescence (%)	0	0	0	0	0	0	0	0
Wild oat growth stages for flamprop-methyl treatments[b]:								
Zadoks DC for main stem only	13 to 14	14 to 31	31	41 to 45	13 to 31	31 to 41	31 to 43	41 to 47
Vegetative (%)	100	83	79	70	98	83	79	64
Elongating (%)	0	17	21	14	2	16	17	19
Booting (%)	0	0	0	16	0	1	4	17
Inflorescence (%)	0	0	0	0	0	0	0	0

[a] Indicates the spraying conditions and growth stages for wild oat plants assigned for full recommended rates of either flamprop-M-methyl or fenoxaprop-p-ethyl.
[b] See Chapter 2.1.1 for method of determining growth stages.

Pots for experiment 92GH were kept inside a glasshouse for the duration from wild oat germination until plant maturity, apart from during the application of herbicides which took place outside the glasshouse. However, the pots for 94GH were kept outside a glasshouse until seed rain (start of seed shedding) (Figure 3.1). The method of herbicide application and assessment of wild oat growth stages was identical to those described in Chapter 2.1.1, except that all wild oat plants in each treatment were assessed. Herbicide spray volumes were 189 and 133 L/ha using 8003 and 8002 Teejet® flat fan nozzles for experiments 92GH and 94GH respectively.

Figure 3.1. Wild oats grown in pots for experiment 94GH maintained and located adjacent to the north facing wall of a glasshouse and showing the automatic watering system at Glen Innes, New South Wales. These plants were subjected to cooler, drier conditions than those noted from inside the glasshouse in experiment 92GH.

Table 3.3. Maintenance and assessments of both pot experiments in relation to dates and/or days after treatment (DAT) for time of application one.

	92GH	94GH
Maintenance:		
Wild oats sown	7.8.92	6.7.94
Thinning wild oats	15 & 27.8.92	9.9.94
Hand weeding	Every assessment date (see below)	
Fertiliser application -1st application	10.9.92 (Nitram®)[a]	21.9.94 (Aquasol®)[b] and approx. every fortnight thereafter.
Non-destructive assessments:		
Panicle production (panicles/plant)	55, 58, 66, 72, 79 & 87 DAT	18, 25, 35, 40, 45, 56 & 69 DAT
Panicles harvested when matured (panicles/plant)	54, 58, 66, 72, 79, 87 & 99 DAT	40, 45, 57 & 70 DAT
Aborted seeds removed (seeds/plant)	N/A	40, 45, 57, 70 & 98 DAT
Destructive assessments:		
Harvest[c]	4.1.93 (99 DAT)	19.1.95 (98 DAT)

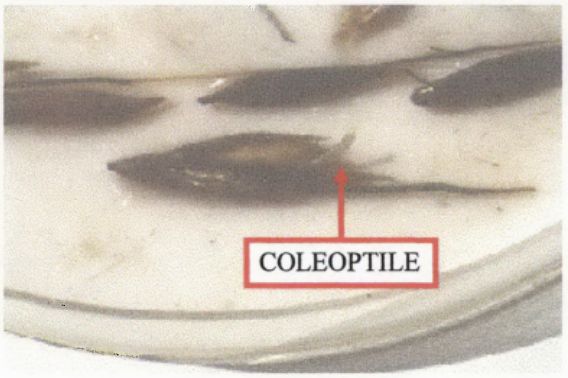
[a] Nitram® applied at 2 g per pot, contains N:P:K equivalent to 34:0:0.
[b] Aquasol® applied at 10 g per 10 L water, contains N:P:K equivalent to 23:4:18.
[c] Harvesting of entire plants to obtain the following wild oat parameters: spikelet seed set (seeds/spikelet), panicle seed set (seeds/panicle), panicle production (panicles/plant), spikelet production (spikelets/plant) and fecundity (seeds/plant). These parameters are outlined in Figure 2.2 and Table 2.2.

Seeds were harvested upon maturity, either just as the seed loosened in the glumes or were collected from the concrete floor in the glasshouse. Pots were well spaced to avoid contamination from adjacent plants. After assessment, seed was bulked for each treatment and stored for at least six months in paper bags at room temperature in an attempt to overcome primary dormancy.

3.3.2. Germination studies

Harvested seed was tested to determine seed viability. Several pilot studies investigated a range of temperature and light conditions along with piercing, de-hulling or pre-soaking seeds with water and incubation in solutions of gibberellic acid, NaOCl, KNO_3, $NaNO_3$, or water to overcome dormancy (Appendix One). It was found that no pre-treatment of seed was beneficial but alternating 12 hour periods at 19°C (light) and 12°C (dark) in cabinets and an incubation solution of 5×10^{-4} M (0.173 g/L) gibberellic acid resulted in the best recorded germination.

Three replicates consisting of 33 seeds chosen at random from bulk seed, were placed in dishes in preparation for viability testing (Figure 3.2). Seeds were arranged on two layers of Whatman No. 1 filter paper and moistened with 5 mL of gibberellic acid solution, in lidded Petri dishes (9 cm diameter). Additional gibberellic acid solution was added as needed. Seed with visible coleoptiles were considered to have germinated (Figure 3.3) and counted and removed from the dish over regular intervals for a total period of 21 days. The total number of seeds germinating was assumed to be an estimate of viability, but likely to underestimate the true viability since seeds that did not germinate may have still had potential to do so.



Figures 3.2 and 3.3. Wild oat seeds imbibing a gibberellic acid solution to stimulate germination and the emergence of the coleoptile, characterising a viable seed that has germinated.

3.3.3. Statistical analyses of data

Angular transformations (in degrees) were required for viability data to homogenise variance. Analysis of other seed production parameters were square root transformed if the variance was not normally distributed. The untreated control treatment in 92GH was analysed as a separate factor, leaving the remaining treatments for factorial effects. The statistical analyses etc. were otherwise as stated in Chapter 2.1.4.

3.4. *Results*

3.4.1. Experiment 92GH

Fenoxaprop-p-ethyl and flamprop-methyl significantly ($P<0.05$) reduced wild oat fecundity (both total seeds and viable seeds/plant) irrespective of time of application (Figures 3.4 (a) and (b)). A significant herbicide by time of application interaction (Appendix Two, Table A.7) was found ($P<0.05$) for both total and viable seeds/plant (Figures 3.4 (a) and (b)). There were no significant differences in fecundity between herbicides when applied at times of application one to four. However, later applications of either herbicide resulted in significantly more seed being produced and fenoxaprop-p-ethyl was less effective than flamprop-methyl ($P<0.05$) in reducing total seeds/plant, but the superior efficacy of flamprop-methyl was only evident at time of application six with respect to viable seeds/plant. These effects for flamprop-methyl represented substantial reductions in wild oat fecundity of between 82.2 and 99.9%, whilst fenoxaprop-p-ethyl reduced fecundity by 58.4 to 99.8%.

A highly significant herbicide by time of application interaction ($P<0.001$) occurred for seed viability (Figure 3.5. (a) and Table A.7). The greatest reduction for seed viability after fenoxaprop-p-ethyl applications was at time of application four (19% tillers elongating), whereas viable seed was least at time of application six (64% elongating / 17% boot) for flamprop-methyl and this effect is likely to have reduced viable seeds/plant (fecundity - Figure 3.4 (b)). Differences in seed viability, between herbicides, were not evident for times of application one, two, three and seven ($P>0.05$).

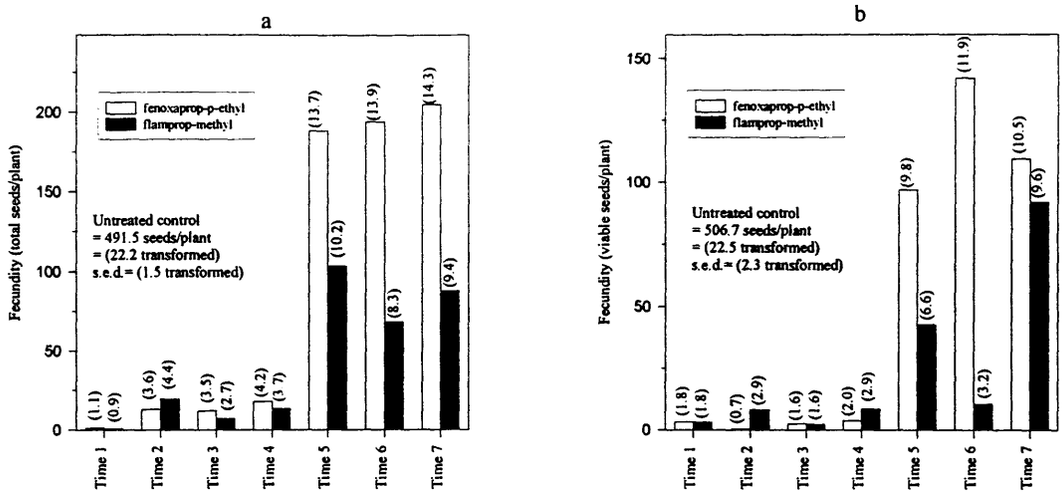


Figure 3.4. Effects of half RDRs of fenoxaprop-p-ethyl and flamprop-methyl on wild oat fecundity ((a) total seeds/plant and (b) viable seeds/plant) for seven times of application ranging across growth stages from late tillering to early panicle emergence. Square root transformed data presented in parentheses.

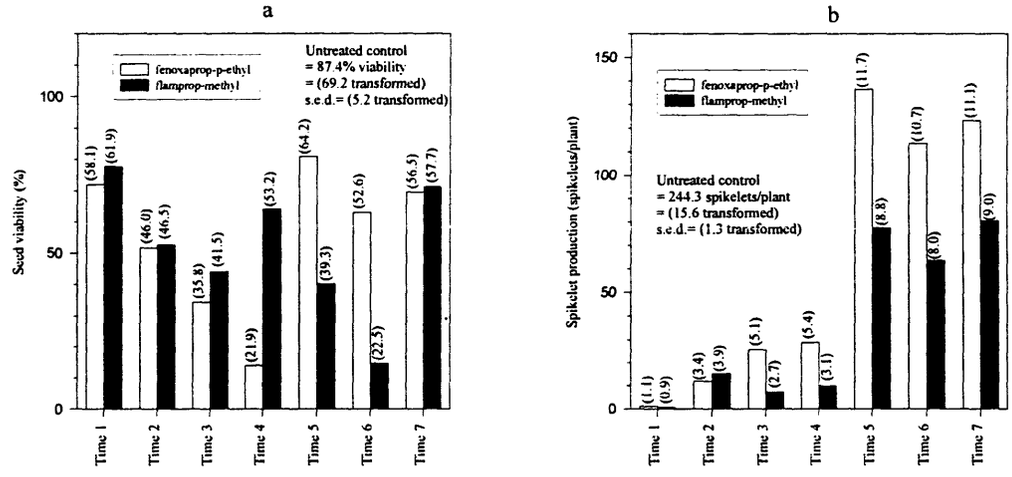


Figure 3.5. Effects of half RDRs of fenoxaprop-p-ethyl and flamprop-methyl on wild oat seed viability (a) and spikelet production (b) for application growth stages ranging from late tillering to early panicle emergence. Angular and square root transformed data presented in parentheses for graphs (a) and (b), respectively.

Spikelet production showed a similar response to those described for wild oat fecundity, with significant herbicide and time effects ($P<0.001$) and a significant drop in efficacy after time of application four (Figure 3.5 (b)). Wild oat spikelet seed set was also significantly less for earlier applications of flamprop-methyl and fenoxaprop-p-ethyl (Figure 3.6 (a)) than for later applications. There was a significant herbicide by time of application interaction ($P<0.05$) for spikelet seed set (Table A.7), with no significant differences between herbicides for times one to four and flamprop-methyl having lower spikelet seed set for the last two times of application.

Panicle seed set was reduced more by flamprop-methyl than by fenoxaprop-p-ethyl for times of application three, five, six and seven ($P<0.05$), resulting in a significant herbicide by time of application interaction ($P<0.01$) (Figure 3.6(b) and Table A.7). The overall effects on panicle production resulted from time of application ($P<0.001$) and herbicide effects ($P<0.05$) (Figure 3.7 and Table A.7). Later times of application and the use of flamprop-methyl resulted in smaller reductions in panicle production and was less effective than fenoxaprop-p-ethyl for reducing panicles/plant at times of application two and five ($P<0.05$).

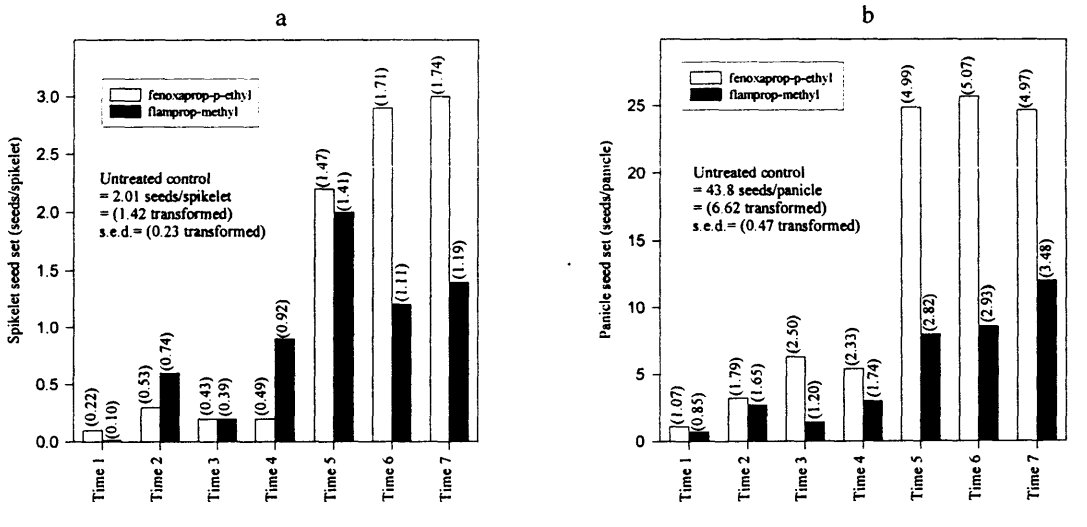


Figure 3.6. Effects of half RDRs of fenoxaprop-p-ethyl and flamprop-methyl on wild oat spikelet seed set (a) and panicle seed set (b) for application growth stages ranging from late tillering to early panicle emergence. Square root transformed data presented in parentheses.

At harvest, most of the plants treated at times of application one and two were dead, whereas most plants for times of application three and four were alive but showed little evidence of active growth (Figure 3.8). Therefore, times of application three and four demonstrate excellent reduction of seed production with minimum plant kill whilst times one and two were more typical of plant kill for early post-emergence applications.

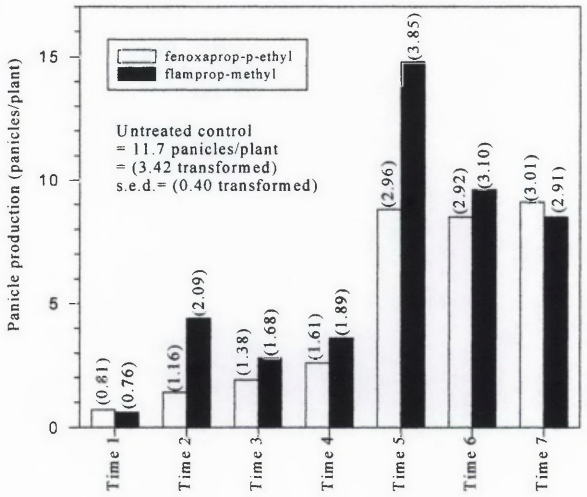


Figure 3.7. Effects of half RDRs of fenoxaprop-p-ethyl and flamprop-methyl on wild oat panicle production for application growth stages ranging from late tillering to early panicle emergence. Square root transformed data presented in parentheses.

Figure 3.8. The efficacy of fenoxaprop-p-ethyl at half RDR applied at growth stages ranging from late tillering to early panicle emergence. From left to right: untreated control, followed by times of application seven through to one.

3.4.2. Experiment 94GH

Fecundity was significantly reduced ($P<0.001$) by half RDRs of fenoxaprop-p-ethyl made at times two and three compared with time one, but this effect was not evident for applications of flamprop-M-methyl at half RDRs (Figures 3.9 (a) and (b), Table A.7). Application of full RDRs of either herbicide, at time of application two resulted in the least fecundity for both total and viable seeds/plant ($P<0.05$). These increased levels of efficacy were also similar for viable seeds/plant.

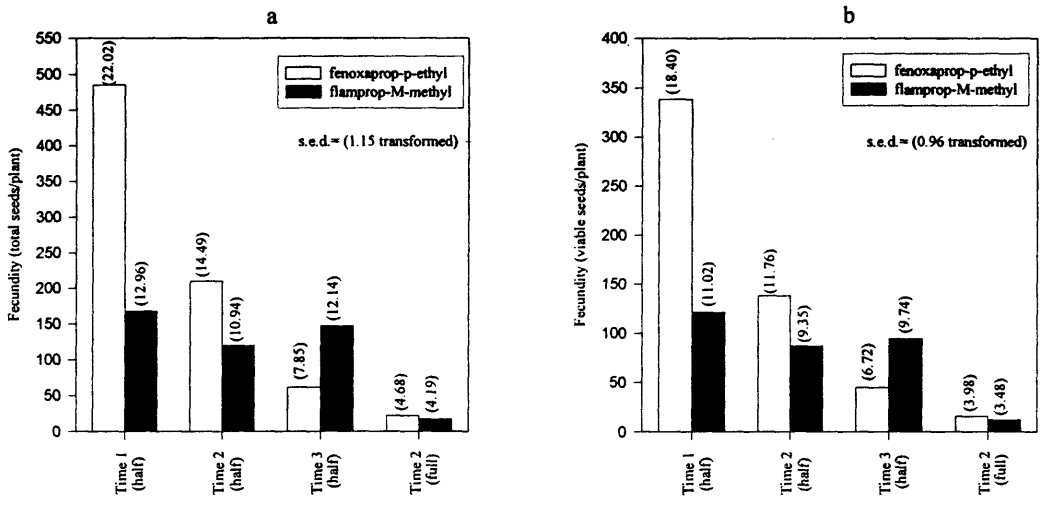


Figure 3.9. Effect fenoxaprop-p-ethyl and flamprop-M-methyl on wild oat fecundity, (a) total seeds/plant and (b) viable seeds/plant. Square root transformed data presented in parentheses.

Fenoxaprop-p-ethyl, regardless of time of application or dose rate, had no significant effect on seed viability (Table 3.4). However, flamprop-M-methyl applied at full RDR for time of application two or at half RDR for time of application three caused significant reductions in seed viability.

Considering the trends in data, not magnitudes, little difference was evident between wild oat fecundity (Figure 3.9) and spikelet production (Table 3.4). This is primarily due to the close relationship between both reproductive parameters, as shown in Figure 2.2, and the factor that links them, spikelet seed set, which did not change significantly for half RDRs over the three

times of application (Table 3.4). The effect of half RDRs on spikelet seed set over time was not significant and was only reduced when full RDRs were used (P<0.001) (Table 3.4).

Table 3.4. Efficacy of flamprop-M-methyl (M) and fenoxaprop-p-ethyl (P) on various wild oat reproductive parameters for three times of application and for full and half RDRs. Transformed data are presented in parentheses.

Wild oat reproductive parameter	Herbicide	Time 1 Half RDR	Time 2 Half RDR	Time 3 Half RDR	Time 2 Full RDR	Significance	s.e.d.
Seed viability (angular % germination)	M	71.8 (57.9)	72.8 (58.6)	62.7 (52.4)	57.7 (49.4)	P<0.001	(1.70)
	P	69.4 (56.4)	65.4 (53.9)	69.4 (56.4)	68.4 (55.8)		
Spikelet production (sq. root spikelets/plant)	M	140.7 (11.86)	102.6 (10.13)	133.6 (11.56)	23.5 (4.85)	P<0.001	(1.03)
	P	304.2 (17.44)	143.5 (11.98)	50.7 (7.12)	14.3 (3.78)		
Wild oat spikelet seed set (seeds/spikelet)	P and M	1.39	1.38	1.19	0.76	P<0.001	0.12
Panicle production (sq. root panicles /plant)	M	22.4 (4.73)	20.1 (4.48)	23.2 (4.82)	6.5 (2.54)	P<0.001	(0.35)
	P	22.3 (4.72)	13.9 (3.73)	7.0 (2.65)	2.9 (1.69)		

Panicle production remained constant for half RDRs of flamprop-M-methyl, irrespective of time of application (Table 3.4). In contrast, significantly lower (P<0.01) panicle production

resulted with progressively later applications of fenoxaprop-p-ethyl at half RDR. Significant further reductions in this parameter resulted from applications of both herbicides at the full RDRs ($P<0.001$). In addition, fenoxaprop-p-ethyl was more effective at reducing panicle production for times of application two and three than flamprop-M-methyl ($P<0.05$).

A. ludoviciana was more susceptible than *A. fatua* to both herbicides, with the former showing consistently greater reductions in seed viability, spikelet production and fecundity (viable seeds/plant). Flamprop-M-methyl reduced fecundity of *A. ludoviciana* more than fenoxaprop-p-ethyl treatments, but no significant differences in fecundity were evident between herbicides for *A. fatua* (Table 3.5). Seed viability of *A. ludoviciana*, after the use of flamprop-M-methyl, was lower than seed treated with fenoxaprop-p-ethyl ($P<0.001$). Furthermore, flamprop-M-methyl had less effect on panicle production for *A. fatua* than fenoxaprop-p-ethyl and no significant difference between herbicides was evident for *A. ludoviciana* ($P>0.001$).

Irrespective of herbicide, fecundity (viable seeds/plant) of both species became less with later applications, using half RDRs, despite the trend for greater levels of seed viability for *A. fatua* with later times of application (Table 3.6). This effect was solely due to fenoxaprop-p-ethyl, as flamprop-M-methyl at half RDR did not change fecundity between times one and three, as mentioned previously (Figure 3.9 (b)). However, due to reductions in viability of *A. ludoviciana* seed with later time of application, the relative drop in fecundity was larger for *A. ludoviciana* than *A. fatua* plants. A relative reduction in fecundity from times one to three was 52.8% for *A. fatua* and 87.2% for *A. ludoviciana.*

Panicle seed set did not change significantly with time, using half RDRs of flamprop-M-methyl, regardless of wild oat species (Figure 3.10). However, time of application had significant effects on panicle seed set when fenoxaprop-p-ethyl was applied, as later applications were more favourable. A complex herbicide by species by time of application interaction was found ($P<0.05$) (Table A.7) and is best illustrated by Figure 3.10.

Table 3.5. Efficacy of fenoxaprop-p-ethyl (P) and flamprop-M-methyl (M) on various wild oat reproductive parameters of *A. fatua* and *A. ludoviciana*, irrespective of herbicide dose rate and time of application. Transformed data are presented in parentheses.

	A. fatua		*A. ludoviciana*			
Wild oat reproductive parameter	P	M	P	M	Significance	s.e.d.
Fecundity (square root viable seeds/plant)	161.0 (12.69)	144.5 (12.02)	59.8 (7.73)	22.8 (4.77)	P<0.05	(0.72)[a] (0.68)[b]
Seed viability (angular % germination)	80.5 (63.80)	83.2 (65.77)	54.3 (47.49)	47.2 (43.37)	P<0.001	(1.32)[a] (1.20)[b]
Spikelet production (square root spikelets/plant)	128.8 (11.35)	159.0 (12.61)	77.6 (8.81)	43.4 (6.59)	P=0.001	(0.60)[a] (0.73)[b]
Panicle production (square root panicles/plant)	10.8 (3.28)	25.7 (5.07)	9.7 (3.12)	10.4 (3.22)	P<0.001	(0.20)[a] (0.25)[b]

[a] s.e.d. for comparing means between species.
[b] s.e.d. for comparing means within species.

Table 3.6. Efficacy of late post-emergence selective herbicides on various wild oat reproductive parameters of *A. fatua* and *A. ludoviciana* and including times of application and herbicide dose rates. Transformed data are presented in parentheses.

	A. fatua				*A. ludoviciana*					
Reproductive parameter	Time 1 Half	Time 2 Half	Time 2 Full	Time 3 Half	Time 1 Half	Time 2 Half	Time 2 Full	Time 3 Half	Signif.	s.e.d.
Fecundity (sqrt. Viable seeds/plant)	324.7 (18.02)	191.3 (13.83)	27.0 (5.19)	153.3 (12.38)	130.0 (11.40)	53.3 (7.28)	5.2 (2.27)	16.6 (4.07)	P=0.001	(0.99)[a] (0.96)[b]
Seed viability (ang. % germination)	75.2 (60.10)	86.5 (68.42)	73.7 (59.15)	89.9 (71.47)	65.8 (54.24)	48.4 (44.07)	51.9 (46.08)	36.8 (37.32)	p<0.001	(1.79)[a] (1.70)[b]
Panicle production (sqrt. Panicles/plant)	25.0 (5.00)	18.6 (4.31)	7.6 (2.76)	21.3 (4.61)	19.9 (4.46)	15.2 (3.90)	2.2 (1.47)	8.2 (2.86)	P<0.05	(0.32)[a] (0.35)[b]

[a] s.e.d. for comparing means between species.
[b] s.e.d. for comparing means within species.

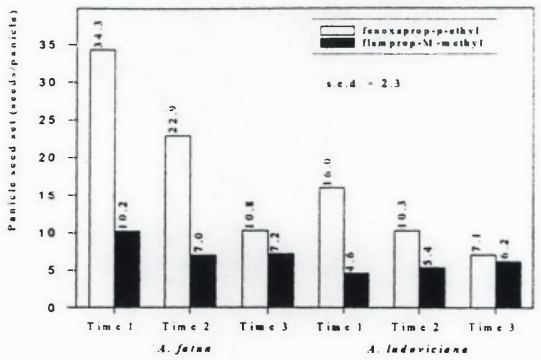


Figure 3.10. Effects of herbicide, wild oat species and time of application on panicle seed set (seeds/panicle) of wild oats. Half RDRs of fenoxaprop-p-ethyl and flamprop-M-methyl are presented but not full RDRs.

3.4.3. Timing of herbicide applications - similarities between experiments

Similarities in wild oat growth stages were evident between times of application four (T4a) and two (T2b) for experiments 92GH and 94GH respectively (Figure 3.11). For these times of application, approximately 20% of tillers were classified as elongating. Likewise growth stage similarities were noted between times of application three (T3a) and one (T1b) for experiments 92GH and 94GH respectively.

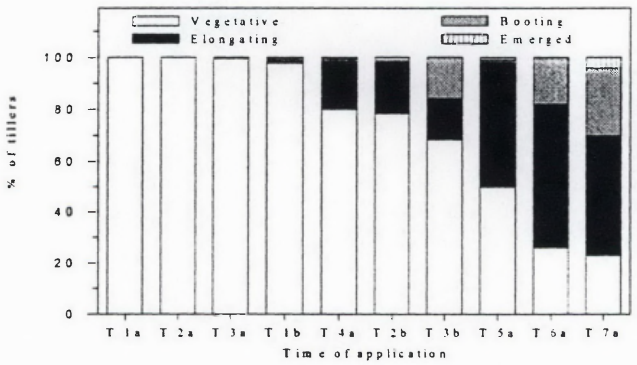


Figure 3.11. Time of application expressed as a proportion of wild oat tillers categorised into four classes, ranging from vegetative to panicle emergence stage, for experiments 92GH and 94GH. Data presented are the averages of *A. fatua* and *A. ludoviciana* (experiment 94 GH) and both herbicide treatments (both experiments). Times of application T 1a to T 7a and times T 1b to T 3b correspond to successive times of application for experiments 92 GH and 94 GH respectively.

3.5. *Discussion*

A strong time of application effect, with a significant drop in herbicide efficacy after time of application four was demonstrated in experiment 92GH, corresponding with early jointing (Zadoks DC = 15 to 37 or 19% tillers elongating, Table 3.1). However, this effect was not as evident for experiment 94GH, as fenoxaprop-p-ethyl efficacy improved for later times of application whereas flamprop-M-methyl efficacy remained relatively constant across the three times of application.

Jeffcoat *et al.* (1977) found the greatest effects of flamprop-methyl on shoot height of wild oats, when applied from two leaf to second node stage under glasshouse conditions, occurred when plants were elongating rapidly, just prior to jointing. Furthermore, it was noted that later applications (one to two node stage) failed to prevent panicle emergence, although shoot height was prevented from increasing four weeks after application. Montazeri (1993) conducted trials in wheat fields to evaluate the effects of fenoxaprop-p-ethyl (0.55 and 0.69 kg a.i./ha) on wild oats at Zadoks DC = 21 and 31. The results indicated that, at both growth stages, fenoxaprop-p-ethyl effectively reduced the biomass and the number of inflorescences. These findings agree closely with the results of the experiments reported this chapter.

With reference to experiment 92GH, fecundity was reduced by between 79 and 86% (total seeds/plant) or between 91 and 98% (viable seeds/plant) when flamprop-methyl was applied to wild oat plants after early booting and before early panicle emergence (predominantly Zadoks DC = 32 to 50). It is possible that flamprop-methyl can give acceptable levels of efficacy compared with fenoxaprop-p-ethyl for later growth stages, but results obtained within this chapter are from one experiment and need to be evaluated further under field conditions. Furthermore, very late applications might cause excessive phytotoxic damage to wheat and this likewise needs to be investigated.

The poor efficacy of fenoxaprop-p-ethyl at time of application one in experiment 94GH, was a likely consequence of frosty conditions. Several severe frosts occurred around the times of application one and two and most of the soil in the pots was frozen for the majority of the day.

Frosting did not occur for experiment 92GH as plants were kept inside. Warnings on labels of both the herbicides used state that it is inappropriate to spray plants stressed by frosty conditions. It is therefore likely that reduction in seed production for fenoxaprop-p-ethyl at half RDR, at times of application one and two in experiment 94GH, would have been much higher than other times of application, if the effect of frost was removed. This effect may have also affected flamprop-M-methyl efficacy, however flamprop-M-methyl was a more reliable herbicide under these conditions and against both wild oat species.

To estimate the effects of frosting, a comparison can be made between fecundities of *A. ludoviciana* in experiment 94GH and wild oat plants (mostly (90%) *A. ludoviciana*) in experiment 92GH at the comparable growth stages of times of application two and four respectively (Figure 3.11). The fecundities of wild oats (total seeds/plant) for half RDRs of fenoxaprop-p-ethyl and flamprop-methyl, at time of application four (experiment 92GH), were 17.8 and 13.4 seeds/plant, respectively. In contrast, wild oat fecundities for half RDRs of fenoxaprop-p-ethyl and flamprop-methyl, at time of application two (experiment 94GH), were 143.8 and 81.7 seeds/plant. Clearly, there were large differences between the two experiments and these differences are likely to be caused by the differences in environmental conditions.

The lower fecundities (seeds/plant) were primarily caused by reductions in the following: spikelet seed set (seeds/spikelet), panicle seed set (seeds/panicle) and panicle production (panicles/plant). Thus the combination of these three parameters contributed to significant reductions in spikelet production (spikelets/plant). The major difference between the two herbicides was a lower panicle seed set (seeds/panicle) for flamprop which was partly offset by greater panicle production (panicles/plant). These differences were common to both experiments and resulted in flamprop generally having slightly better efficacy than fenoxaprop-p-ethyl. These effects can be related back to the chemical activity of each herbicide. Flamprop-methyl restricts cell elongation of wild oat apical meristems, causing reduced internode length (Morrison *et al.* 1979) and delayed development of panicles (Jeffcoat *et al.* 1977), which are likely to be responsible for smaller panicles. Plants treated with flamprop in both experiments were generally stunted but some were capable of weak regrowth, consisting of numerous small tillers producing low quantities of seed. Fenoxaprop-

p-ethyl treated plants took longer to produce herbicide symptoms than flamprop, and fenoxaprop-p-ethyl had less effect on earlier emerging panicles compared with flamprop. These panicles were generally larger and produced more seed than later maturing panicles (data not presented). However, fenoxaprop-p-ethyl symptoms persisted longer and limited the amount of regrowth under the growing conditions where nutrients and water were non-limiting and there was an absence of inter-specific competition.

There were significant differences between the two wild oat species, in relation to fecundity and other plant reproductive parameters. Averaged over times of application and rates, flamprop-M-methyl reduced fecundity (viable seeds/plant) of *A. ludoviciana* more than fenoxaprop-p-ethyl (Table 3.5). From this, the selection of flamprop-M-methyl over fenoxaprop-p-ethyl in regions where *A. ludoviciana* dominates, such as the northern grain belt, would appear to be logical. In mixed infestations of *A. fatua* and *A. ludoviciana*, it is possible that selection for increased dominance *A. fatua* could occur following the use of either herbicide since *A. fatua* was generally more tolerant of herbicides than *A. ludoviciana.* No literature could be found that reports differences between late post-emergence herbicides in preventing seed production between wild oat species, and none is available that investigates herbicide application as a plant kill tactic. Nonetheless, Mansooji *et al.* (1992) have found different levels of herbicide resistance between certain collections of the two wild oat species (*A. ludoviciana* and *A. fatua*).

Plant fecundity was generally lower in experiment 92GH than for experiment 94GH. Contributing factors may have been the cold frosty conditions for experiment 94GH, as outlined previously, and possibly humidity effects on experiment 92GH since plants were wholly maintained in a glasshouse. Improved herbicide efficacy can be obtained from glasshouse grown plants (Coleman-Harrell and Lee 1978) due to improved herbicide uptake under higher humidity and temperature conditions (Veerasekaran *et al.* 1977; Retzinger 1981; Kirkwood 1990; Kloppenburg and Hall 1990; Bouma and Wartena 1994). It is uncertain from these experiments that these results, particularly the effect of time of application, could be related back to commercial field situations. The enhanced herbicide efficacy may have been offset by lack of any inter or intra-specific competition in the pots.

The time of application of selective post-emergence herbicides that resulted in optimal reductions in wild oat seed production was approximately the early jointing growth stage (Zadoks DC = 31 to 32) or 20% of wild oat tillers elongating. This wild oat growth stage, to be referred to as the apparent optimum time (growth stage), was selected as a result of a compromise between delaying any herbicide application, with respect to reducing seed production, for as long as possible to target a majority of cohorts, particularly those that may be recruited late under field situations, but early enough to avoid significantly large reductions in herbicide efficacy. This apparent optimum time was determined primarily from experiment 92GH since results from experiment 94GH were confounded by unfavourable conditions around herbicide application. Before a more reliable definition of apparent optimum wild oat growth stage can be determined, the effect of herbicide time of application must be investigated in field situations over a range of environmental conditions. This was the basis of the work reported in the succeeding chapter.

Chapter 4. Field studies: Determining apparent optimum growth stage for late post-emergence applications of selective herbicides to wild oats

4.1. *Introduction*

Environmental and competitive conditions within field crops are vastly different to those experienced when plants are grown in pots. Under the pot conditions described in Chapter Three, water and nutrients were made non-limiting and as plants were grown in monoculture there were no inter-specific and minimal intra-specific interference. Jeffcoat *et al.* (1977), Anon. (1990) and Lemerle *et al.* (1992) have suggested that competitive crops are likely to reduce wild oat growth after herbicide application. Wild oats generally have staggered and/or late emergence patterns in the field (Thurston 1961, 1963) whereas emergence in the two pot experiments (Chapter Three) was deliberately synchronised. Additionally, elimination of moisture stresses should have enabled maximum herbicide uptake and efficacy (Xie *et al.* 1995, 1996). Therefore, confirmation of the apparent optimum growth stage for minimising seed production found under the reported pot conditions needs to be confirmed for field / crop situations.

In Chapter Three it was concluded that the wild oat growth stage for apparent optimum reductions in seed production with fenoxaprop-p-ethyl and flamprop, under pot conditions, was early jointing stage or Zadoks DC = 31. This agrees closely with Jensen's (1990) findings for flamprop-M-isopropyl tested under field conditions in Denmark, but there are no reports on the optimum growth stage for applications in field crops of fenoxaprop-p-ethyl or its analogues. It has been established in overseas research that applications of fenoxaprop-p-ethyl (0.55 and 0.69 kg a.i./ha) to wild oats at Zadoks DC = 21 and 31 effectively reduced panicle production, but the work did not measure seed production or test a wider range of growth stages than those in Chapter Three (Montazeri 1993). A glasshouse experiment by Jeffcoat *et al.* (1977) using flamprop-methyl, identified the optimum growth stage as the phase of growth when wild oats are elongating rapidly (jointing or Zadoks DC = 30 to 39), assessing shoot height as the key characteristic. However, many researchers have used the crop growth stage as the indicator (Warley *et al.* 1974; Smith and Livingston 1978; Friesen 1987) and some have not measured wild oat seed production as an outcome (Warley *et al.*

1974; Jeffcoat *et al.* 1977). Work conducted in Greece by Skorda (1974), concluded that applications of flamprop-methyl at 0.6 kg a.i./ha applied at the end of tillering (Zadoks DC = 30) gave the highest and most consistent control which corresponded to a 99% reduction in seed populations.

The work reported in this chapter sets out to fill gaps in the knowledge of how the aforementioned overseas work relates to Australian conditions and to assess whether the findings of the pot experiments (Chapter Three) hold up under field conditions.

4.2. *Aims*

The primary objective of the work reported in this chapter was to determine the apparent optimum growth stage for the application of fenoxaprop-p-ethyl and flamprop that maximises the reduction in wild oat seed production within commercial wheat crops. The secondary objective was to establish if the apparent optimum growth stage varied for different herbicide dose rates. Assessments were made on a range of seed production parameters, similar to those measured in the pot experiments, with the aim of identifying those that may contribute significantly to a reduction in seed production and to compare the relative effects on fecundity under pot and field conditions.

4.3. *Materials and methods*

Four field experiments were undertaken in commercial wheat crops coded IN92RXT, CR92RXT, IN93RXT and SM94RXT. The general methodology for these field experiments is described in Chapter Two and additional details of the four experiments, including experimental design, past and present paddock details and harvesting dates, are given in Table 4.1. Herbicide application and growth stage details are given in Table 4.2 for experiment IN92RXT, Table 4.3 for experiment CR92RXT and Table 4.4 for experiments IN93RXT and SM94RXT. All experiments listed in Table 4.1 had fenoxaprop-p-ethyl and flamprop as the main herbicide treatments, with three treatment replications. All experiments included half and full RDRs of fenoxaprop-p-ethyl and flamprop but experiment IN93RXT also included the application of quarter RDRs (Chapter Two and Table 4.1). An untreated control was used

for each herbicide sub-plot in experiment SM94RXT and individual untreated control treatments were used in the other experiments.

Experiment IN92RXT had infestations of *Polygonum aviculare* (wireweed) averaging 200 plants/m^2 and *Hirschfeldia incana* (Buchan weed) at 2 plants/m^2 which emerged late in the season. These weeds were uniformly distributed across the experimental site and could not be controlled with a late herbicide application because of chemical incompatibility problems with fenoxaprop-p-ethyl and flamprop-methyl. A solution of MCPA 500 amine (100 mL a.i./10 L water) was used to spot spray *Silybum marianum* (variegated thistle) and *Rapistrum rugosum* (turnip weed) in experiment CR92RXT.

Table 4.1. Historical and paddock details, and experimental design of field experiments IN92RXT, CR92RXT, IN93RXT and SM94RXT.

	Experimental code			
Paddock records	IN92RXT	CR92RXT	IN93RXT	SM94RXT
Paddock history	3rd year of wheat	2nd year of wheat	2nd year of wheat	2nd year of wheat
Wheat cultivar	'Hartog'	'Yallaroi'	'Owlet'	'Suneca'
Sowing date	23.6.92	23.4.92	7.6.93	3.6.94
Sowing rate (kg/ha)	45	45	40	40
Harvest date for wheat	18.12.92	23.11.92	Not harvested	16.11.94
Seed indexing date	Not indexed	Not indexed	4.11.93	17.10.94
Hand harvest date for wild oat	18.12.92	23.11.92	3.12.93	11.11.94
Wild oat densities at spraying (plants/m^2)	8 to 38	11 to 80	8 to 33	39 to 73
Fertilisers (kg/ha)	Urea = 90 (N[a] = 41.4)	Nil	Urea = 70 (N[a] = 32.2)	Nil
Experimental design	Randomised complete block	Randomised complete block	Randomised complete block	Split plot: herbicides main plots & dose rate & time of app'n as sub plots
Times of application	Five	Five	Three	Four
Proportion of RDRs applied	Half and full	Half and full	Quarter, half and full	Half and full

[a] Equivalent units of nitrogen.

Combined analyses of relative reductions in seed production were achieved by fitting a semi-logarithmic regression model to pooled data from experiments IN92RXT, CR92RXT and

IN93RXT for each combination of rate (half and full RDR) and herbicide. Data from experiment SM94RXT were not included in the combined analyses due to the severe drought conditions experienced which affected the results abnormally.

Table 4.2. Herbicide application details, including growth stage of wild oats and wheat, and the spraying conditions at the time of application for experiment IN92RXT.

Application	Time 1	Time 2	Time 3	Time 4	Time 5
Spraying conditions:					
Date	8.9.92	17.9.92	1.10.92	7.10.92	13.10.92
Days after sowing	93	102	116	122	128
Time	2:15 pm	9:50 am	3:30 pm	3:00 pm	2:00 pm
Temp. Wet bulb (°C)	12.5	9.0	11.5	14.0	14.0
Temp. Dry bulb (°C)	22.0	12.5	20.5	23.0	21.0
Relative humidity (%)	30	63	31	34	46
Cloud cover (%)	25	15	10 (high)	20	15
Wind direction	NW/N	W	NW	N	E/NE
Wind speed (m/s)	Moderate	1.5 to 7.8	1.0 to 3.5	0 to 0.9	0.7 to 1.6
Average wind speed (m/s)	Moderate	2.5	1.6	0.4	1.2
Growing conditions	Excellent, growing actively	Excellent, growing actively	Excellent, growing actively	Good to excellent, growing actively	Good, growing actively
Wild oat growth stages[a] (averaged for both flamprop-methyl and fenoxaprop-p-ethyl treatments):					
Zadoks DC for main stem only	13 to 30	14 to 32	15 to 53	14 to 55	31 to 59
Vegetative (%)	99	79	53	48	32
Elongating (%)	1	21	42	38	44
Booting (%)	0	0	4	10	14
Inflorescence (%)	0	0	1	3	9
Wheat growth stages[a] (averaged for both flamprop-methyl and fenoxaprop-p-ethyl treatments):					
Zadoks DC for main stem only	14 to 30	14 to 31	31 to 33	31 to 43	32 to 61
Vegetative (%)	99	67	42	34	26
Elongating (%)	1	33	58	66	63
Booting (%)	0	0	0	0	9
Inflorescence (%)	0	0	0	0	2

[a] See Chapter 2.1.1 for method of determining growth stages.

Table 4.3. Herbicide application details, including growth stage of wild oats and wheat, and the spraying conditions at the time of application for experiment CR92RXT.

Application	Time 1	Time 2	Time 3	Time 4	Time 5
Spraying conditions:					
Date	1.7.92	22.7.92	12.8.92	19.8.92	26.8.92
Days after sowing	69	90	111	118	125
Time	2:30 pm	1:30 pm	11:00 am	2:00 pm	12:50 pm
Temp. Wet bulb (°C)	16.5	10.0	14.0	9.5	10.5
Temp. Dry bulb (°C)	20.5	16.0	19.5	17.0	18.0
Relative humidity (%)	66	47	54	36	38
Cloud cover (%)	5	5	50 (high)	Nil	20
Wind direction	NW	SW	NW	SW	SE
Wind speed (descriptive)	Slight to moderate	Slight to moderate	Moderate	Slight to moderate	Slight to moderate
Growing conditions	Excellent, growing actively	Excellent, growing actively	Excellent, growing actively	Good, growing actively	Good, growing actively
Wild oat growth stages[a] (averaged for both flamprop-methyl and fenoxaprop-p-ethyl treatments):					
Zadoks DC for main stem only	13 to 31	13 to 32	15 to 55	31 to 57	31 to 57
Vegetative (%)	99	83	55	37	42
Elongating (%)	1	17	42	47	40
Booting (%)	0	0	2	13	7
Inflorescence (%)	0	0	1	3	10
Wheat growth stages[a] (averaged for both flamprop-methyl and fenoxaprop-p-ethyl treatments):					
Zadoks DC for main stem only	13 to 14	15 to 31	14 to 33	16 to 37	32 to 34
Vegetative (%)	100	90	73	39	14
Elongating (%)	0	10	27	61	86
Booting (%)	0	0	0	0	0
Inflorescence (%)	0	0	0	0	0

[a] See Chapter 2.1.1 for method of determining growth stages.

The use of Teejet® flat fan nozzles, size 8002 was common to all herbicide treatments with herbicide spray volumes of 189 L/ha (experiment IN92RXT and CR92RXT), 156 L/ha (experiment IN93RXT) and 133 L/ha (experiment SM94RXT).

Table 4.4. Herbicide application details, including growth stage of wild oats and wheat, and the spraying conditions at the time of application for experiments IN93RXT and SM94RXT.

	Experiment IN93RXT			Experiment SM94RXT			
Application	Time 1	Time 2	Time 3	Time 1	Time 2	Time 3	Time 4
Spraying conditions:							
Date	4.9.93	16.9.93	23.9.93	1.9.94	5.9.94	8.9.94	15.9.94
Days after sowing	89	101	108	90	94	97	104
Time	12:00 pm	11:10 am	2:40 pm	1:30 pm	2:30 pm	5:00 pm	4:40 pm
Temp. Wet bulb (°C)	9.0	10.5	11.0	13.0	14.5	11.5	12.5
Temp. Dry bulb (°C)	15.0	14.5	18.0	20.0	24.0	20.0	22.5
Relative humidity (%)	45	62	42	45	32	34	28
Cloud cover (%)	Nil	10	60	Nil	50 to 70	10	Nil
Wind direction	E	W/NW	N/NE	W/NW	N/NW	No breeze	SW
Wind speed (m/s)	1.2 to 3.1	2.0 to 5.3	0.0 to 1.3	0.3 to 1.3	2.4 to 4.9	0.0	0.3 to 1.0
Average wind speed (m/s)	1.7	3.7	0.4	1.0	3.5	0.0	0.5
Growing conditions	Excellent, growing actively	Excellent, growing actively	Excellent, growing actively	Weak plants recovering after rain	Plants recovering & growing quickly	Actively growing	Actively growing
Wild oat growth stages[a] (averaged for both flamprop-M-methyl and fenoxaprop-p-ethyl treatments):							
Zadoks DC for main stem only	14 to 32	13 to 32	12 to 43	14 to 51	13 to 49	14 to 54	15 to 65
Vegetative (%)	98	69	51	68	55	43	43
Elongating (%)	2	31	48	28	35	45	38
Booting (%)	0	0	1	4	10	11	13
Inflorescence (%)	0	0	0	0	0	1	6
Wheat growth stages[a] (averaged for both flamprop-M-methyl and fenoxaprop-p-ethyl treatments):							
Zadoks DC for main stem only	14 to 31	31 to 32	31 to 34	14 to 32	30 to 33	31 to 33	32 to 34
Vegetative (%)	97	50	32	60	48	28	28
Elongating (%)	3	50	68	40	52	72	72
Booting (%)	0	0	0	0	0	0	0
Inflorescence (%)	0	0	0	0	0	0	0

[a] See Chapter 2.1.1 for method of determining growth stages.

4.4. *Results*

4.4.1. Experiment IN92RXT

All applications of flamprop-methyl or fenoxaprop-p-ethyl significantly ($P<0.05$) reduced seed production relative to the untreated control, except at time of application five; the greatest reductions occurred at times one to three for both herbicides (Figure 4.1 (a)). Fenoxaprop-p-ethyl treatments reduced seed production more than flamprop-methyl for the first two applications resulting in a significant ($P<0.05$) herbicide by time of application interaction (Table A.8). The relative reduction in seed production (% of untreated), between times of application one and three, showed that fenoxaprop-p-ethyl and flamprop-methyl treatments ranged from 88.5 (394 seeds/m^2) to 98.0% (68 seeds/m^2) and 88.3 (402 seeds/m^2) to 93.6% (220 seeds/m^2), respectively. Relative reductions in seed production after time of application three had a wider range of 41.3 to 73.6%. Time of application three corresponded to wild oat plants with 47% of tillers at the elongation stage or more advanced (Zadoks DC = 15 to 53) (Table 4.2). For fenoxaprop-p-ethyl treatments, seed production was significantly less ($P<0.05$) at time of application two, compared with time three.

Full RDRs of fenoxaprop-p-ethyl and flamprop-methyl significantly reduced seed production ($P<0.05$) more than half RDRs at all times of application except time five. Half RDRs failed to reduce seed production compared with the untreated control at application four and five while all applications at full RDR significantly ($P<0.05$) reduced seed production, resulting in a highly significant ($P<0.001$) rate by time of application interaction (Table A.8 and Figure 4.1(b)).

There was no significant difference ($P>0.05$) in seed production between full RDRs for times of application one and two (Figure 4.1(b)). However, seed production was progressively and significantly higher ($P<0.05$) for each later application. For half RDRs, seed production was reduced more ($P<0.05$) for time of application two compared with time one. This level of seed production was not significantly different at time of application three but reductions in seed production were less for times of application four and five. Calculating reductions in seed production (back transformed data) relative to the untreated control, from Figure 4.1(b),

reductions ranged from 76.1 to 89.2% and 93.5 to 99.3% for half and full RDRs respectively, between times of application one and three.

The principal timing effects on other wild oat seed production parameters were a rate by time of application interaction on panicle density ($P<0.001$) (Figure 4.2(a)) and herbicide by time of application interaction for panicle seed set ($P<0.05$) (Figure 4.2(b) and Table A.8).

There were similarities in the rate by time of application interaction for both seed production and panicle density (Figures 4.1(b) and 4.2(a)). Panicle density was reduced more using full RDRs compared with half RDRs for all times of application, apart from time of application five ($P<0.05$). Time of application two resulted in the lowest panicle density for half RDRs and significant increases occurred after the same time of application for full RDRs. Wild oat plants treated at time of application two had 21% of tillers at the elongation stage (Zadoks DC = 14 to 32 (Table 4.2)).

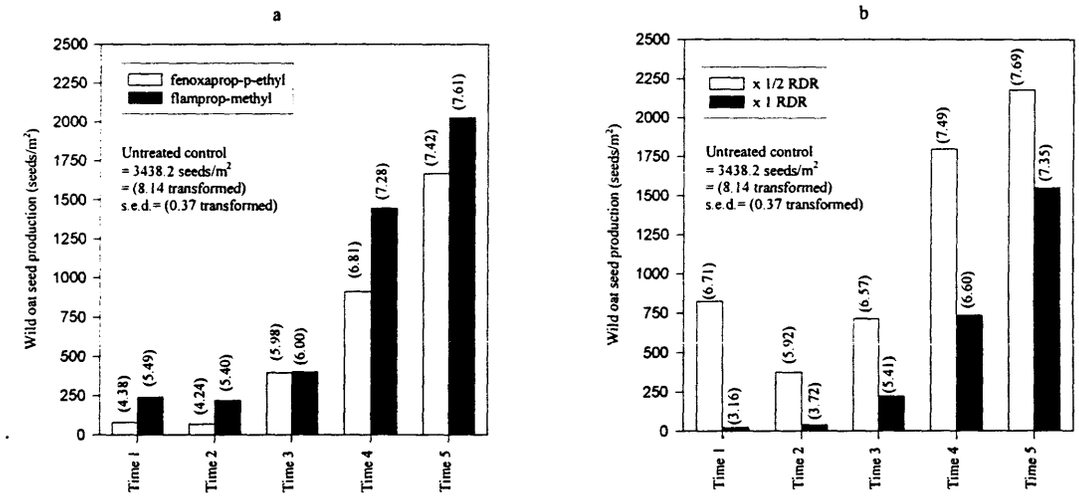


Figure 4.1. Effect of fenoxaprop-p-ethyl and flamprop-methyl (a) and herbicide rate (b) over time on wild oat seed production (seeds/m^2) for experiment IN92RXT. Data presented were covariate adjusted. Logarithmic transformed data presented in parentheses.

All applications of flamprop-methyl and fenoxaprop-p-ethyl, irrespective of time of application and rate, reduced panicle seed set ($P<0.05$) (Figure 4.2(b)). Wild oat panicle seed set was consistently reduced more by flamprop-methyl than fenoxaprop-p-ethyl, irrespective

of herbicide dose rate. The lowest panicle seed set for flamprop-methyl was at time of application three, which was significantly lower than times of application one, two and five. Panicle seed set for fenoxaprop-p-ethyl was the lowest at times of application one and four whilst the remaining applications resulted in similar panicle seed sets ($P<0.05$).

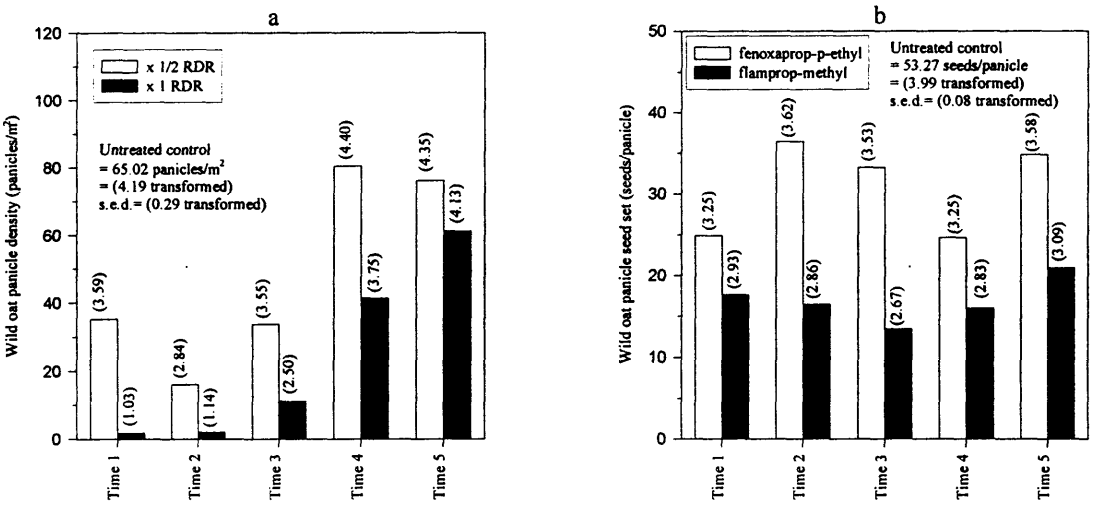


Figure 4.2. Effect of herbicide rate over time of application on (a) wild oat panicle density at harvest (panicles/m^2) (covariate adjusted) and the effect of fenoxaprop-p-ethyl or flamprop-methyl over time of application on (b) panicle seed set (seeds/panicle) for experiment IN92RXT. Logarithmic transformed data presented in parentheses.

4.4.2. Experiment CR92RXT

Two significant time interactions were found for experiment CR92RXT, in relation to seed production. They were the time by herbicide ($P<0.05$) and time by rate ($P<0.001$) interactions (Table A.8). This was in agreement with the interactions found for experiment IN92RXT, reported in Chapter 4.4.1.

Seed production for times of application after time two was significantly ($P<0.05$) higher compared with earlier times of application, regardless of herbicide (Figure 4.3(a)). A comparison of time of application, from two to three, resulted in 99.4 to 93.2% and 96.7 to 58.7% reductions of seed production compared with the untreated control for fenoxaprop-p-ethyl and flamprop-methyl, respectively. This equates to seed production of 29 to 307

seed/m^2 (fenoxaprop-p-ethyl) and 146 to 1,554 seeds/m^2 (flamprop-methyl). Fenoxaprop-p-ethyl was most effective at time of application one whilst flamprop-methyl was most effective at times one and two (Figure 4.3(a)). Apart from the application of flamprop-methyl, at time of application three, all herbicides applied prior to time four resulted in at least 93% reduction of seed production compared with the untreated control (averaging herbicide rates over times of application).

Application of half RDRs, regardless of herbicide, at time one resulted in significantly ($P<0.05$) lowered seed production in comparison with full RDRs applied at times of application three to five (Figure 4.3(b)).

The herbicide by time of application interaction ($P<0.05$) that affected panicle density (Figure 4.4(a)), was due mainly to flamprop-methyl being less effective at time of application three compared with earlier times of application. A difference in panicle density between flamprop-methyl and fenoxaprop-p-ethyl was detected prior to time of application four with flamprop-methyl associated with more panicles/m^2. Regardless of RDR (half and full), flamprop-methyl treatments prior to time of application three had similar panicle densities. The increased number of wild oat panicles produced from flamprop-methyl treatments at time of application three (Figure 4.4(a)) was not offset by reduced panicle seed set (Figure 4.5) and therefore resulted in the significant increase in seed production (Figure 4.3(a)).

Panicle density of wild oats resulting from treatments applied at half RDRs and for time of application one was significantly less ($P<0.05$) than either herbicide rate applied after time of application two (Figure 4.4(b)). There was no significant difference ($P>0.05$) in panicle density between half RDRs at times of application one and two, and likewise for full RDRs at the same times of application. A significant interaction ($P<0.001$) between time of application and herbicide rate was detected (Table A.8). Average panicle density resulting from the application half RDR of both herbicides at time of application two was less than applications of either RDRs applied at later application growth stages, except for full RDRs at time of application three (Figure 4.4(b)).

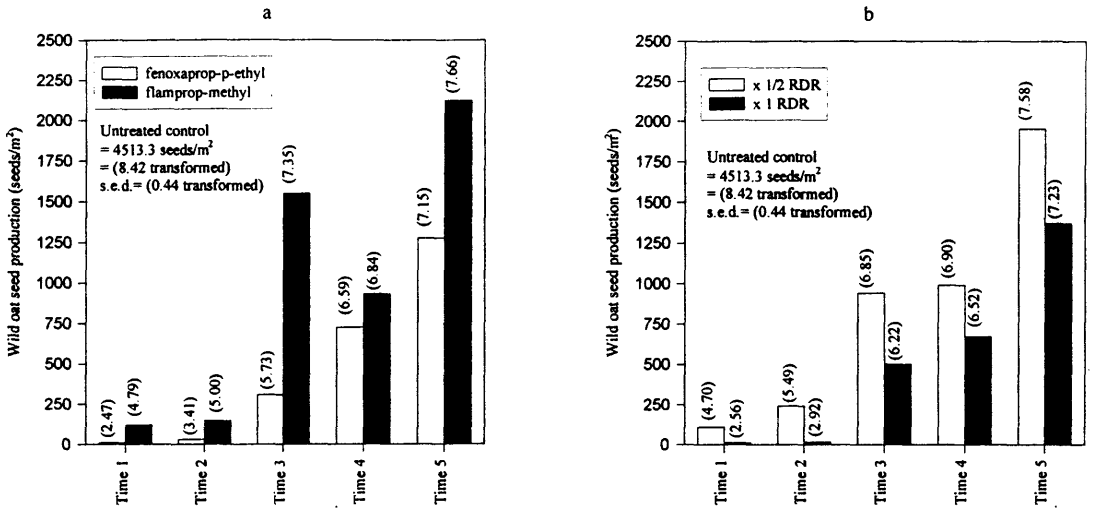


Figure 4.3. Effect of fenoxaprop-p-ethyl and flamprop-methyl application over time (a) and the effect of herbicide rate over time (b) on wild oat seed production (seeds/m^2) for experiment CR92RXT. Data presented was covariate adjusted. Logarithmic transformed data presented in parentheses.

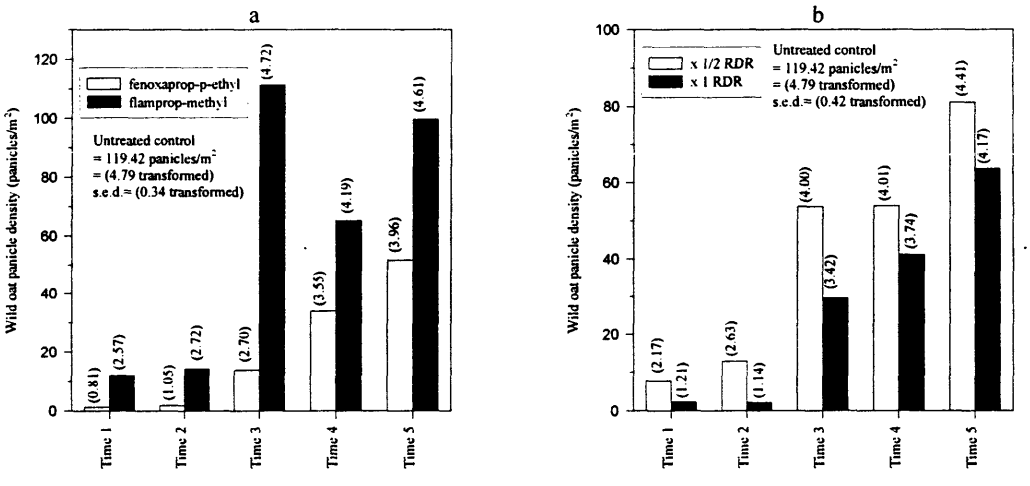


Figure 4.4. Effect of fenoxaprop-p-ethyl and flamprop-methyl (a) and herbicide rate (b) over time on wild oat panicle density at harvest (panicles/m^2) for experiment CR92RXT. Logarithmic transformed data presented in parentheses.

A highly significant (P<0.001) time of application by rate by herbicide interaction occurred for wild oat panicle seed set (Figure 4.5 and Table A.8). The effect of flamprop-methyl rate over all times of application did not have any significant effect on panicle seed set but applications prior to time five resulted in less seeds/panicle than the untreated control plants (P<0.05). Half RDRs of fenoxaprop-p-ethyl were ineffective at early times of applications but using the full RDR at time of application one was very effective in reducing wild oat panicle seed set.

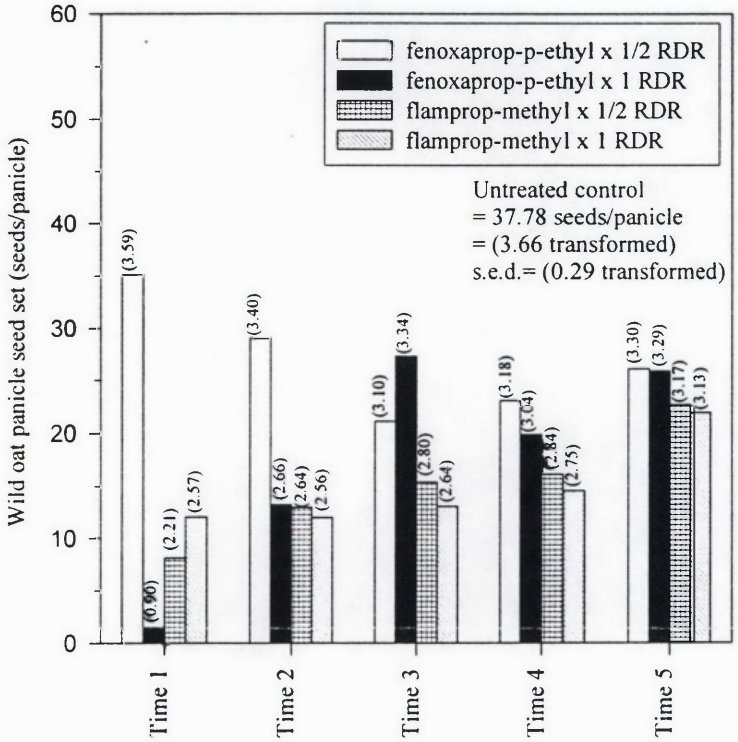


Figure 4.5. Interaction between herbicide, time of application and herbicide rate on wild oat panicle seed set (seeds/panicle) for experiment CR92RXT. Logarithmic transformed data presented in parentheses.

4.4.3. Experiment IN93RXT

Rate by herbicide interactions were recorded in this experiment for a number of parameters, including seed production, panicle density and spikelet seed set (Tables 4.5 and A.8). Seed

production was not reduced by quarter RDRs of either herbicides at any time of application ($P<0.05$). Least seed was produced following the application of half RDR at time of application one and for full RDRs for applications times one and two, all achieving greater than 70% reductions in seed production (Table 4.5).

Wild oat panicle density was reduced relative to the untreated control using full RDRs applied at times one and two (Table 4.5). Spikelet seed set was not significantly ($P>0.05$) reduced by any time of application or herbicide rate. Spikelet seed set from full RDRs at time of application two was significantly less than all other time of application / herbicide rate combinations except for half RDRs at time of application two and full RDRs at time of application three ($P<0.05$).

Herbicide by time of application interactions were detected for wild oat panicle density ($P<0.01$), panicle production ($P<0.05$) and panicle seed set ($P<0.05$) (Figures 4.6(a), (b) and (c)). Wild oat panicle density was significantly reduced compared with the unreated control ($P<0.05$) for fenoxaprop-p-ethyl, regardless of rates, at times of application one and two (Figure 4.6(a)). Panicle density was not significantly ($P>0.05$) affected by type of herbicide at times of application one and three. However, a significant difference ($P<0.01$) was recorded at time two, such that fenoxaprop-p-ethyl caused lower panicle density than flamprop-M-methyl. Time of application two corresponded to 31% tillers elongating or Zadoks DC = 32 (Table 4.4). A similar effect was seen in experiment CR92RXT, with large numbers of panicles being produced for growth stages between 17% tillers elongating (Zadoks DC = 32) and 45% tillers elongating or more advanced (Zadoks DC = 55), as shown in Chapter 4.4.2 (Figure 4.4(a)).

Panicle production was not affected by herbicide or dose rate at time of application three, but was significantly reduced compared with the untreated control ($P<0.05$) by fenoxaprop-p-ethyl at times of application one and two Figure 4.6(b).

Table 4.5. Effect of application rate and time on various wild oat reproductive parameters, irrespective of type of herbicide, for experiment IN93RXT. Transformed data are presented in parentheses.

	Untreated control	Time 1 ¼ RDR	Time 1 ½ RDR	Time 1 x1 RDR	Time 2 ¼ RDR	Time 2 ½ RDR	Time 2 x1 RDR	Time 3 ¼ RDR	Time 3 ½ RDR	Time 3 x1 RDR	Significance	s.e.d.
Wild oat seed production (ln seeds/m^2)	1229 (7.12)	1421 (7.26)	252 (5.54)	123 (4.82)	1146 (7.05)	576 (6.36)	145 (4.98)	1201 (7.09)	1073 (6.98)	550 (6.31)	P<0.05	(0.50)[b] (0.41)[c]
Reduction in seed production (% of untreated)	0.0	-15.6[a]	79.5	90.0	6.8	53.1	88.2	2.3	12.7	55.2		
Wild oat panicle density (ln panicles/m^2) -covariate adjusted	49.0 (3.91)	68.2 (4.24)	21.2 (3.10)	12.2 (2.58)	47.8 (3.89)	45.1 (3.83)	16.9 (2.89)	53.2 (3.99)	61.9 (4.14)	46.1 (3.85)	P=0.01	(0.42)[b] (0.35)[c]
Wild oat spikelet seed set (seeds/spikelet)	1.75	1.85	1.87	1.84	1.91	1.71	1.57	1.74	1.76	1.65	P<0.05	0.10[b] 0.08[c]

[a] Negative numbers signify greater seed production relative to the untreated control.
[b] s.e.d. to compare means for herbicide dose rates and times of application with untreated control.
[c] s.e.d to compare means between herbicides dose rates and times of application.

Fenoxaprop-p-ethyl applied at time one significantly reduced ($P<0.05$) panicle seed set, compared with the untreated control, averaged over herbicide rates, whilst flamprop-M-methyl consistently reduced panicle seed set relative to the untreated control seed set for all times of application (Figure 4.6(c)).

Wild oat fecundity was significantly reduced ($P<0.05$) by applications of herbicides at times one and two Figure 4.6(d). Fecundity from untreated control plants was 57.0 seeds/plant (Figure 4.6(d)) and contrasts with untreated control plants for experiment 92GH of 491.5 seeds/plant (Figure 3.4(a)). Growth stages for times of application one and two were very similar to those of times of application one and three in experiment 94GH (Table 4.6). Wild oat fecundities from experiment IN93RXT were much lower than those from experiment 94GH. This trend was consistent for the four treatments common to both experiments.

Table 4.6. Comparisons between wild oat plant fecundity of field experiment IN93RXT and pot experiment 94GH for treatments applied at similar growth stages.

	Experiment IN93RXT				Experiment 94GH			
Treatment	Time of application	% tillers ≥ elongating	Zadoks DC	Fecundity (seeds/plant)	Time of application	% tillers ≥ elongating	Zadoks DC	Fecundity (seeds/plant)
Half RDR fenoxaprop-p-ethyl	One	2	32	19.0	One	3.5	31	484.9
Half RDR fenoxaprop-p-ethyl	Two	31	32	30.0	Three	30.5	45	61.6
Half RDR flamprop-M-methyl	One	2	32	24.9	One	3.5	31	168.0
Half RDR flamprop-M-methyl	Two	31	32	25.0	Three	30.5	45	147.4

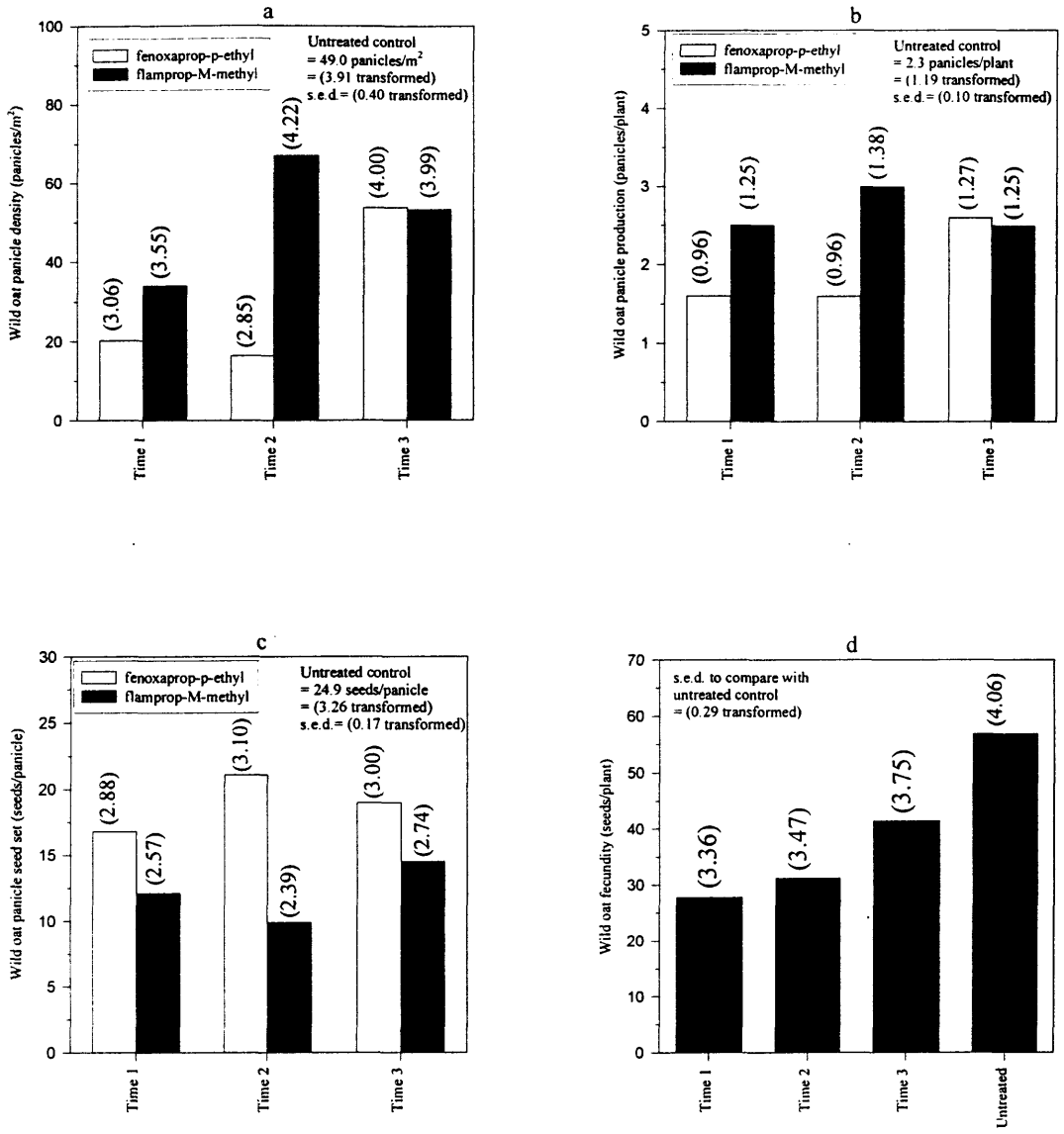


Figure 4.6. Experiment IN93RXT: Herbicide and time of application interactions for wild oat panicle density (a), panicle production (b) and panicle seed set (c). Effect of time of application on wild oat fecundity (d), irrespective of herbicide. Wild oat fecundity (d) was also averaged across herbicide rates. Data presented in Figure 4.6 (a) were covariate adjusted and logarithmic transformed data presented in parentheses.

4.4.4. Experiment SM94RXT

Fenoxaprop-p-ethyl applied at time one reduced seed production and panicle density ($P<0.05$), whereas flamprop-M-methyl reduced seed production at all times of application (Table 4.7).

Table 4.7. Experiment SM94RXT: Effect of flamprop-M-methyl, fenoxaprop-p-ethyl and time of application on various wild oat reproductive parameters, irrespective of herbicide rate. Transformed data are presented in parentheses.

	Untreated control fenoxaprop	Untreated control flamprop	Time 1	Time 2	Time 3	Time 4	Time 1	Time 2	Time 3	Time 4	Significance	s.e.d.[a]	s.e.d.[b]
			fenoxaprop-p-ethyl				flamprop-M-methyl						
Wild oat seed production (ln seeds/m^2) - covariate adjusted	2898 (7.97)	2773 (7.93)	1285 (7.16)	2721 (7.91)	3065 (8.03)	1973 (7.59)	652 (6.48)	1388 (7.24)	1003 (6.91)	1748 (7.47)	P<0.001	(0.20)[c] (0.17)[d]	(0.20)[c] (0.18)[d]
Reduction in seed production (% of respective untreated)[f]	0	0	55.7	6.1	-5.8	31.9	76.5	49.9	63.8	37.0		(0.13)[e]	(0.14)[e]
Wild oat panicle density (ln panicles/m^2) -covariate adjusted	127.1 (4.85)	114.8 (4.75)	78.9 (4.40)	127.5 (4.86)	151.6 (5.03)	119.4 (4.81)	145.9 (4.99)	106.4 (4.70)	96.2 (4.57)	152.2 (5.05)	P<0.001	(0.16)[c] (0.14)[d] (0.11)[e]	(0.17)[c] (0.15)[d] (0.12)[e]
Wild oat plant density (ln plants/m^2) -covariate adjusted	45.9 (3.85)	40.1 (3.72)	30.3 (3.44)	39.6 (3.70)	50.4 (3.94)	39.2 (3.70)	50.6 (3.94)	32.4 (3.51)	32.1 (3.50)	43.2 (3.79)	P<0.001	(0.20)[c] (0.17)[d] (0.14)[e]	(0.21)[c] (0.18)[d] (0.15)[e]
Wild oat fecundity (ln seeds/plant)	63.1 (4.16)	69.6 (4.26)	42.8 (3.78)	69.1 (4.25)	61.0 (4.13)	50.7 (3.95)	75.6 (4.34)	42.9 (3.78)	31.4 (3.48)	40.6 (3.73)	P<0.001	(0.19)[c] (0.17)[d] (0.14)[e]	(0.19)[c] (0.16)[d] (0.13)[e]
Wild oat panicle production (ln panicles/plant) - covariate adjusted	2.8 (1.35)	2.8 (1.36)	2.7 (1.30)	3.3 (1.45)	3.0 (1.39)	3.1 (1.42)	2.9 (1.36)	3.4 (1.48)	3.0 (1.38)	3.6 (1.53)	P<0.01	(0.11)[c] (0.09)[d] (0.08)[e]	(0.11)[c] (0.09)[d] (0.08)[e]
Wild oat panicle seed set (ln seeds/panicle)	23.5 (3.20)	24.8 (3.25)	16.2 (2.85)	20.8 (3.08)	19.5 (3.02)	16.4 (2.86)	25.7 (3.29)	13.2 (2.65)	10.2 (2.41)	11.7 (2.54)	P<0.001	(0.16)[c] (0.14)[d] (0.13)[e]	(0.14)[c] (0.12)[d] (0.10)[e]
Wild oat spikelet seed set (seeds/spikelet)	1.88	1.97	1.86	1.93	1.90	1.82	2.07	1.77	1.60	1.72	P<0.001	0.09[c] 0.09[d] 0.08[e]	0.07[c] 0.06[d] 0.05[e]

[a] s.e.d. to compare means across herbicides.
[b] s.e.d to compare means within herbicides.
[c] s.e.d. to compare between untreated control means.
[d] s.e.d. to compare means for time of application with untreated control means.
[e] s.e.d to compare means between times of application.
[f] Negative numbers signify greater seed production relative to the respective untreated control.

The greatest reduction in seed production relative to the untreated control (76.5%) resulted from flamprop-M-methyl applied at time one and was significantly better than other herbicide / time of application combinations ($P<0.05$). The reduction in seed production by fenoxaprop-p-ethyl treatments at time of application one was associated with significantly ($P<0.05$) lower wild oat fecundity and plant density at harvest. Lower seed production with flamprop-M-methyl, for times of application two to four, appeared to result from a combination of lower plant fecundity, spikelet seed set and panicle seed set (Table 4.7). Despite very dry conditions prior to herbicide application and that all applications were made past the apparent optimum application growth stage (Zadoks = 31 or 20% tillers elongating), in relation to the pot studies, wild oats exhibited typical flamprop symptoms (Figure 4.7). These included general stunting of plant, necrosis of leaf tips sometimes extending to the swollen sheath, production of non-viable, light coloured and unfilled seed (if applied to wild oats in boot) without killing the plants.

4.4.5. Combined analyses of timing experiments

Of a number of statistical models tested, a semi-logarithmic regression model fitted to the half RDRs gave the best fit and accounted for 25.3% and 40.3% of variation for flamprop and fenoxaprop-p-ethyl, respectively (Figure 4.8(a) and (b)). Fenoxaprop-p-ethyl at full RDR had a fitted relationship that also accounted for 41.5% of variation (Figure 4.8(d)), similar to the lower rate, whereas the fit for full RDRs of flamprop accounted for 68.4% of the variation (Figure 4.8(c)).

Reductions in seed production were calculated from the logarithmic relationships in Figure 4.8, for the apparent optimum growth stage (80% tillers vegetative and 20% elongating) determined from Chapter Three. Half RDRs of either herbicide were calculated to reduce seed production by 67 and 59% for fenoxaprop-p-ethyl and flamprop respectively. By comparison, full RDRs were calculated to reduce seed production by 79 and 74% for fenoxaprop-p-ethyl and flamprop respectively.

Figure 4.7. Symptoms of a wild oat plant treated with full RDR of flamprop-M-methyl applied to wild oats in the late boot stage (Zadoks DC ≈ 47) or time of application three, from experiment SM94RXT.

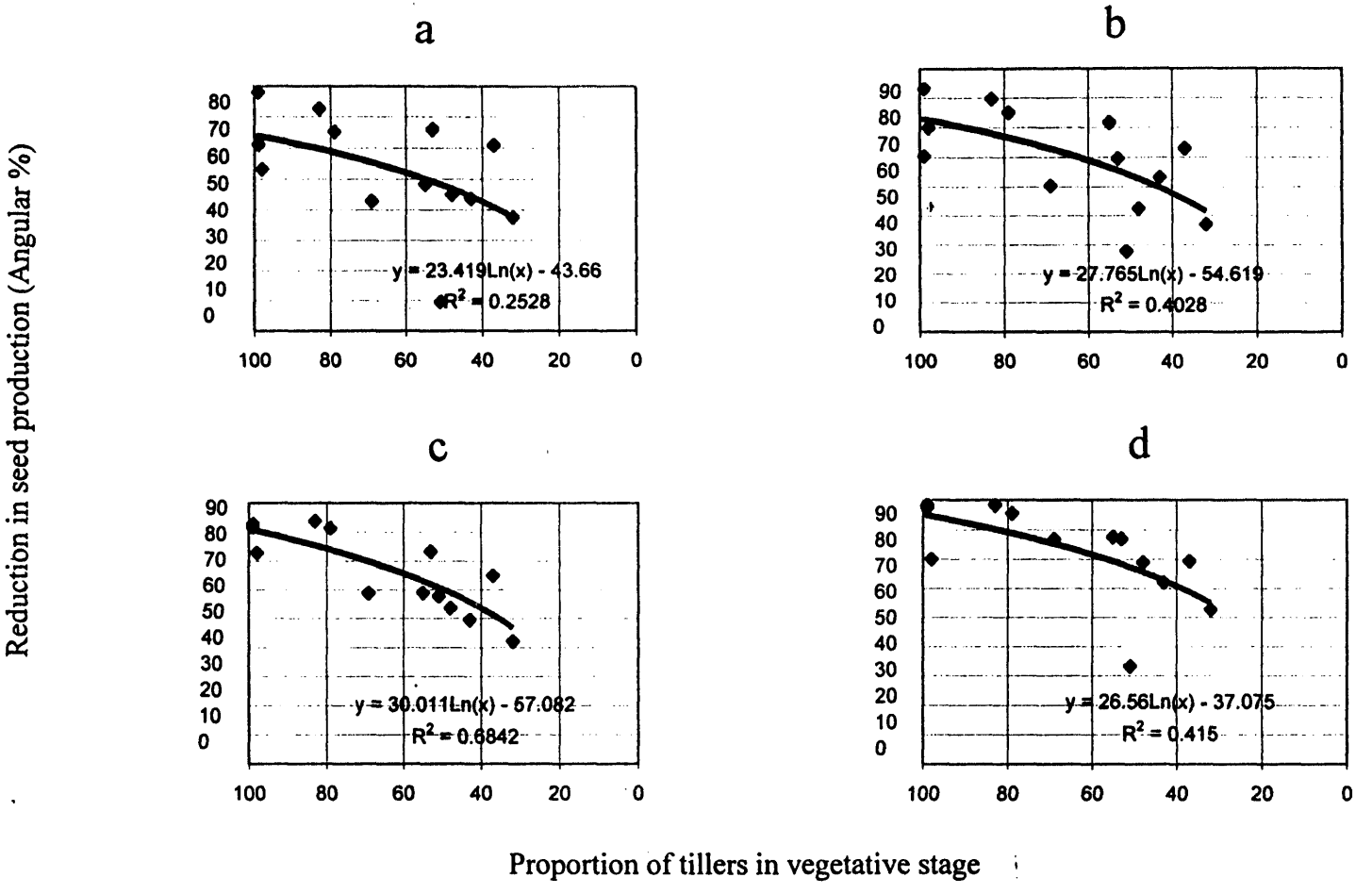


Figure 4.8. Combined analyses of experiments IN92RXT, CR92RXT and IN93RXT: Relationship between percent reduction in wild oat seed production relative to untreated control (angular transformed) for half and full RDRs of flamprop (a) and (c) and fenoxaprop-p-ethyl (b) and (d), respectively.

4.5. *Discussion*

After testing a range of times of application and dose rates of fenoxaprop-p-ethyl and flamprop in wheat across contrasting sites and seasons, a consistent trend emerged regarding the apparent optimum time of application in relation to wild oat growth stage.

The apparent optimum growth stage identified in experiment IN92RXT, was associated with 21% tillers elongating (Zadoks DC = 14 to 32) for fenoxaprop-p-ethyl whereas it was 47% tillers elongating or more advanced (Zadoks DC = 15 to 53), for flamprop-methyl. However, upon investigating the rate by application timing effects, the apparent optimum growth stage was 21% tillers elongating (Zadoks DC = 14 to 32). Slightly different effects were recorded for experiment CR92RXT. Zadoks DC = 13 to 31 or 1% tillers elongating was identified as the apparent optimum growth stage for fenoxaprop-p-ethyl and 17% tillers elongating (Zadoks DC = 13 to 32) for flamprop-methyl.

In experiment IN93RXT, the greatest reduction in seed production occurred with half RDRs of herbicides when applied to wild oats with 2% tillers elongating (Zadoks DC = 14 to 32). The use of full RDRs extended the apparent optimum growth stage to between 2% and 31% tillers elongating (Zadoks DC = 13 to 32). Finally in experiment SM94RXT, both herbicides reduced seed production most when applied to wild oats with 32% tillers elongating or more advanced (Zadoks DC = 14 to 51). This was despite the plants being moisture stressed by drought prior to spraying. Stress imposed by limiting moisture was identified as a cause of lower efficacy of flamprop-isopropyl (Jeffcoat and Harries 1975) and fenoxaprop-ethyl (Xie *et al.* 1996).

In summary, the apparent optimum wild oat growth stage, across experiments varied within the range of 2 to 31% tillers elongating, with an average of approximately 20% tillers elongating, corresponding to Zadoks DC = 14 to 32. This growth stage corresponds closely to the apparent optimum of 19% tillers elongating or Zadoks DC = 15 to 37, found under controlled conditions (experiment 92GH, Chapter Three).

Although this apparent optimum growth stage accounts for both herbicides at half and full RDRs, there is some evidence that half RDRs need to be applied slightly earlier than full RDRs for maximum reductions in seed production. In two experiments (IN92RXT and CR92RXT) half RDRs had apparent optimum application growth stages identical to full RDRs, but in one experiment (IN93RXT) the half RDR had an earlier apparent optimum growth stage (2% tillers elongating or Zadoks DC = 32). The use of quarter rates at or near the putative apparent optimum growth stage failed to impact on seed production. Flamprop-methyl had a later apparent optimum growth stage, compared with fenoxaprop-p-ethyl, on two occasions (experiments IN92RXT and CR92RXT) and was identical once (experiment SM94RXT).

The apparent optimum growth stage found in the reported experiments agrees closely with that reported by Skorda (1974). Skorda's field studies in Greece found that lowest seed production occurred if flamprop-methyl was applied at a higher dose of 0.6 kg a.i./ha to wild oats at the end of tillering (Zadoks DC = 30) and resulted in the seed production being reduced by 99%. Flamprop-methyl applied at similar growth stages in the present study reduced wild oat seed production by 94 to 97% (average of half and full RDRs) for experiments IN92RXT and CR92RXT, respectively. The apparent optimum application growth stage is also very similar to that stated by Jeffcoat *et al.* (1977) for glasshouse conditions, which stated rapidly elongating wild oat plants were more susceptible to flamprop-methyl. Similarly, Jensen (1990) found in Denmark that flamprop-M-isopropyl applied to wild oats in barley at Zadoks DC = 31 resulted in minimal seed production.

In view of the findings reported in the literature and those found in the present experiments it can be concluded that the apparent optimum growth stage would appear to correspond with 20% tillers elongating or approximately Zadoks DC = 31 to 32. This growth stage is around the middle of the range of growth stages that consistently maximised the reduction in seed production.

Fenoxaprop-p-ethyl and flamprop had different effects on wild oat reproductive components. Flamprop caused the development of smaller panicles (lower panicle seed set), compared with fenoxaprop-p-ethyl treatments but was generally offset by larger numbers of panicles (panicle

density). This effect generally diminished with application at later growth stages. On a few occasions, the use of flamprop-M-methyl caused lower spikelet seed set (seeds/spikelet). Both of these herbicides applied near the apparent optimum growth stage reduced wild oat plant fecundity (seeds/plant) by affecting all of the various reproductive components.

There were large differences in wild oat fecundity (seeds/plant) between field and pot experiments. Considering both herbicides and both half and full RDRs, wild oat fecundities from the pot experiment 94GH were between two and 25 times greater than those of similar treatments applied at comparable growth stages for field experiment IN93RXT. Thus there appears to be a strong influence of inter-specific competition on the efficacy of herbicides to reduce seed production under field conditions. This appears to have offset any influence of less optimal conditions for herbicide uptake and activity under field conditions relative to more ideal conditions in pots (Chapter Three). It is likely these conditions in pots resulted, in part, from rapid regrowth of treated plants, causing significant increases in seed production. Despite these differences between pot and field conditions, all experiments gave best reductions in seed production at similar growth stages.

Jensen (1990) treated *A. fatua* plants at Zadoks DC = 31 with flamprop-M-isopropyl (610 g a.i./ha), an analogue of flamprop-methyl used extensively in Europe for wild oat control in barley crops. Although effects on seed emergence were not assessed, no emergence occurred in the field the following autumn and spring, indicating that either seed production and/or viability may have been markedly reduced. However, Jensen did note that all applications of flamprop-M-isopropyl, including rates of 152, 305 and 610 g a.i./ha for Zadoks DC = 31 and 39, significantly lowered seed weight.

Research on seed of other weed species has shown strong positive correlations between seed size and germinability, such that larger seeds have greater germination percentages than smaller seeds (Schaal 1980; Hendrix 1984; Stanton 1984; Chandra Babu *et al.* 1990). Although seed size or weight was not measured in the pot studies (Chapter Three) or field experiments, it is likely that the significantly lower levels of viability measured in the pot experiments for most application growth stages, was partly due to reduced seed size. Observations from all of the field experiments showed that several panicles were prevented

from emerging from the sheath and where they did seeds were often sterile (Figure 4.7). From other observations it was noted that regrowth of panicles late in the season were very small and most seed produced from these panicles appeared much smaller than untreated seed, or were not filled.

The consequences of large seeds are the ability to emerge from greater depths (Dalianis 1980; Wulff 1986) and seedlings produced are generally more vigorous (Twamley 1967; Dalianis 1980; Wulff 1986; Chandra Babu *et al.* 1990). These larger seedlings are more likely to have a greater competitive ability (Stanton 1984), possibly causing greater crop yield losses.

Results presented in this chapter focused mainly on seed production, expressed as total seeds/m^2 and does not take into account any loss of viability due to physiological or herbicidal effects on seeds. Seed viability could not be determined in the reported experiments because resources did not allow detailed seed collection. However, research by Jensen (1990) indicated that large reductions in seed viability (up to 100%) were recorded following application of flamprop-M-iospropyl at 610 g a.i./ha applied at Zadoks DC = 31. The findings reported from the present experiments may therefore underestimate the total impact of herbicides on viable seed production. Although this needs to be quantified, such studies are difficult to undertake because of problems with collecting seed in the field.

Reductions in seed production from half RDRs at the apparent optimum wild oat growth stage were estimated from the fitted logarithmic relationships in Figure 4.8. These values (67% fenoxaprop-p-ethyl, 59% flamprop) were below the critical value of 70% estimated by simulation modelling (Pandey and Medd 1990), as the level of reduction in seed production required to bring about a decline in wild oat populations, regardless of crop yield. However, similar estimations from the logarithmic relationship suggest that applications of full RDRs are likely to result in reduction of seed production greater than 70%. However, as herbicide dose rates can be reduced by synergistic effects of adjuvants (Sharma *et al.* 1976; Taylor *et al.* 1982; Turner and Ayres 1985; Chow 1988; Harker 1992; Holloway and Edgerton 1992; Smith and Vanden Born 1992; Ryan 1993) this possibility needs to be further investigated, and this is the subject explored in the following chapter. Immediate economic savings could be obtained if the use of adjuvants, in combination with lower herbicide rates, could obtain levels of efficacy

comparable with those from higher herbicide rates with no addition of adjuvant. It is possible that applications of herbicides made at the apparent optimum application growth stage will return an immediate economic return from wheat yield conservation, since Winfield and Caldicott (1975), Anderson and Howat (1990) and Koscelny and Peeper (1997) reported moderate to high levels of crop yield conservation relative to the untreated controls for herbicide treatments that were generally applied to mid tillering wild oats, a growth stage that is not too dissimilar to the apparent optimum application growth stage. Furthermore, the apparent optimum growth stage for reducing wild oat seed production is soon after the latest registered time of application for early post-emergence control of wild oats to conserve crop yield (Puma®S label (fenoxaprop-p-ethyl)- the wild oat late tillering stage).