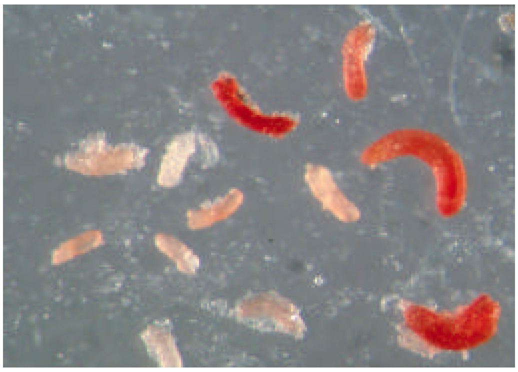

Chapter 5

Seasonal changes in the dormancy and evolution of viability of buried seeds of herbicide resistant and susceptible *Papaver rhoeas* L. population in North-eastern Spain (Catalonia)

Seasonal changes in the dormancy and evolution of viability of buried seeds of herbicide resistant and susceptible *Papaver rhoeas* L.

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Summary

Seed lots of three *Papaver rhoeas* L. populations in two cases resistant to tribenuron-methyl and to 2.4-D and in one case susceptible to herbicides were buried at 2, 8 and 20 cm depth in Lleida (Catalonia, Spain). Monthly and after one germination cycle twice monthly exhumation was conducted during 31 months and germination capacity as well as seed viability assessed.

A similar annual dormancy cycle was described for each population and burial depth in the three years. Maximum germination was found between September and December, almost no germination occurred between February and May. The burial depth influenced the germination cycle mainly in the first months, so that the shallowest buried seeds lost initial dormancy very fast.

One of the resistant populations generally germinated most, probably due to its different origin but not to its resistance characteristics, as the other two populations behaved very similar between each other. Fatal germination was found since 9 months after burial in the 2 cm depth treatment, mainly.

A short-time burial experiment revealed that buried P. rhoeas seeds lost primary dormancy very quickly regardless of burial depth reaching between 31 and 44% germination one month after burial versus 5 to 8% germination when kept in pots in a warehouse.

Final viability determined with the tetrazolium assay after 31 months was found between 63 and 99% depending on the depth and on the population. For cultural weed control, ploughing should thus not be conducted frequently, as most exhumed seeds were still capable to germinate 31 months after burial.

Keywords: burial, dormancy, fatal germination, herbicide resistance, *Papaver rhoeas* L., tetrazolium, viability.

Introduction

Papaver rhoeas L. is a winter annual plant, which is present in every continent but is most abundant in Europe, where it originated (Holm *et al*., 1997). This species prefers generally calcareous soils and does not grow on clay and peat soils being often associated with cereal crops (McNaughton and Harper, 1964). In North-eastern Spain, *P. rhoeas* is the most important broadleaf weed infesting winter cereals occurring in 39% of surveyed fields (Riba *et al.*, 1990).

The interest in deepening into the knowledge of *P. rhoeas* biology is even bigger since appearance of herbicide resistance in the study area forces farmers to adopt integrated weed management practices. Herbicide resistance to the auxin nalog herbicide 2.4-D has been reported in 1992 (Taberner *et al*, 1992), to the sulfonylurea tribenuron-methyl since 1995 (Taberner *et al.*, 1995) and a first population resistant to both herbicides described in 1998 (Claude *et al.*, 1998). The affected area in North-eastern Spain growing since then (A. Cirujeda and A. Taberner, unpublished data).

Freshly harvested *P. rhoeas* seeds are normally highly dormant (McNaughton and Harper, 1964). This has also been observed in numerous populations collected in North-eastern Spain (A. Cirujeda and A. Taberner, unpublished data). Seeds are kidney-shaped and their size is supposed to remain constant over a wide range of conditions measuring approximately 0.7 to 1 mm length and 0.5 mm wide (Holm *et al.*, 1997).

Several experiments have been conducted in different countries aiming to describe the seed behaviour of *P. rhoeas* in different soil and burial conditions.

In France, Barralis *et al*. (1988) found 10.5% of the *P. rhoeas* seeds initially buried still intact after five years of burial in soil in 5 to 20 cm depth. They classified *P. rhoeas* as a weed species with a slow decrease of germination capacity in time.

In the United Kingdom Froud-Williams *et al.* (1984) found still 21% of the initial *P. rhoeas* seeds after two years of burial in 5 cm depth and subjected to cultivation and 36% at the same depth in undisturbed conditions. These percentages were higher than for surface placed seeds. Also in the United Kingdom, Roberts and Feast (1973) found an annual pattern of exponential decrease of the viable seeds in cultivated soil conditions ranging between 20 and 26%. They found a 21% of viable *P. rhoeas* seeds in undisturbed soil conditions after six years of burial and 7% in cultivated conditions.

In Denmark, buried *P. rhoeas* seeds were buried by Kjær (1940) in 25 cm depth during 5 years observing still 30% of germination capacity in field conditions after exhumation.

These authors are coincident with the fact that *P. rhoeas* seeds are able to survive during several years making seed bank depletion very difficult even if seed-rain is avoided. However, data dispersal and absence of experiments conducted for *P. rhoeas* germination behaviour in Mediterranean conditions justifies the present work.

The populations used in the present study were multiple resistant to 2.4-D and to tribenuron-methyl. Generally, no important differences in biological behaviour between susceptible and ALS-resistant weed species have been observed (Saari *et al*., 1994). An exception was faster germination detected in ALS-resistant *Lactuca serriola* seeds towards susceptible seeds. Fitness penalty was quoted on 2.4-D resistant *Sinapis arvensis* but not for other species (reviewed by Coupland, 1994).

A similar case to the present *P. rhoeas* populations is a *Galium spurium* population found to be resistant to the ALS-inhibitor triasulfuron and to the auxin-type herbicide quinclorac (Hall et al., 1998). No different behaviour compared to susceptible biotypes was quoted in this case.

The aims of the present work were to determine the dormancy cycles of susceptible and herbicide resistant *P. rhoeas* populations in order to find out when germination is expected to occur.

It was also targeted to describe the viability of *P. rhoeas* seeds buried at different depths after several months in order to know if placing the *P. rhoeas* seeds in depth enhances rotting of the seeds in Mediterranean conditions. This could give information on the time requested for ploughing again once the seeds had been placed in depth by ploughing or cultivation. If differences between susceptible and herbicide resistant populations were detected, this could have repercussions on weed management.

Material and Methods

Plant material

Three populations of *P. rhoeas* collected in North-eastern Spain (Catalonia) were chosen for the study. Seeds of two confirmed resistant populations to both herbicides tribenuron-methyl and to 2.4-D from Baldomar and Savallà del Comptat codified as B/98 and S/98, respectively, and one non-treated susceptible population from Algayón codified as A/98 were collected during two years in July 1998 and 1999. The same populations received the code A/99, B/99 or S/99 when collected in 1999.

After drying at room temperature during 10 days they were stored in plastic pots and kept in a warehouse at 20ºC. In order to determine initial seed viability, seeds were sown on agar medium containing 0.8 g GA_3 L^{-1}. Germination rate reached 90-100% in all three populations in both years. The 1000 seeds weight in g are shown in Table 5.1.

Table 5.1.: 1000 seed weight of three *Papaver rhoeas* populations collected in 1998 and in 1999 in North-eastern Spain (Catalonia). Mean ± SD.

Population	1998	1999
A	0.1251±0.00163	0.0921±0.00384
B	0.1053±0.00181	0.1150±0.00182
S	0.1211±0.00170	0.1306±0.00350

In spite of the different climatic conditions between Spain and United Kingdom, these data are similar to the 0.1189 ± 0.0071 of the 1000 seed weight found by McNaughton and Harper (1964) in populations collected in United Kingdom.

Long-time burial experiment

A part of the seeds collected in July 1998 was used for the burial experiment. Samples containing 50 seeds each were buried in fine-mesh gauze bags the 24th July 1998 at 2, 8 and 20 cm depth in a seed free silt-loam soil in Lleida (Spain). 2 cm depth would imitate non-tillage situation. 8 cm is the depth of cultivation, 20 cm is the depth after ploughing. Three replicates of the three populations in each three depths were buried in 31 individual lots.

During the first 16 months, samples were exhumed monthly, afterwards in two months intervals. The total field surface in which bags were buried measured about 3 m x 3 m and was manually kept clean of weeds. Bags were exhumed, seeds were taken out of the bags, washed in water and sown in Petri dishes on a 1.3 % agar medium with 2 g KNO_3 l^{-1} and placed randomly in a growing chamber under controlled temperature and light conditions. This medium composition was the optimum found for *P. rhoeas* when natural germination wanted to be recorded (Cirujeda *et al.*, 1999).

Due to the presence of fungi 0.2% benzimidazole was added reducing lack of germination caused by fungi. The temperature and light conditions were 20 μmol S^{-1} m^{-2} of fluorescent light during 16 hours at 20ºC and darkness at 10ºC during 8 hours, which was found optimum for *P. rhoeas* germination (A. Taberner, unpublished data). The dishes were placed randomly in the growth chamber and germination was recorded every week. Final data corresponded to the 21 days assessment as previous experiments showed that main germination occurred in this period while virtually no germination occurred later. This data is similar to the value found by Bishop and Pemberton (1996) who described that *P. rhoeas* reached maximum germination after 18 days.

The followed methodology of exhumation and placing the seeds on agar medium in a growth chamber under controlled conditions aims to describe what would be expected to happen if seeds in the soil were suddenly placed into optimal germination conditions. It does not reproduce the germination habit of *P. rhoeas* in field conditions but the dormancy stage of each moment.

At some of the exhumation dates, seed viability was determined. After 21 days, the non-germinated seeds were subjected to the tetrazolium bioassay. This was performed in October 1998, January 1999, August 1999, June 2000 and February 2001. In spite of washing the seeds after exhumation and adding the fungicide, some samples presented high fungal contamination when placed on the agar. In these cases, seeds were tested after 10 to 15 days after sowing already trying to avoid fungi to kill the seeds. When no problems appeared, they were kept until the end of the germination experiment.

The tetrazolium viability test was carried out following the rules of the Seed Testing Analysis described by the Spanish Ministry of Agriculture (MAPA, 1987). The seeds were gently cut without damaging the embryo before being introduced in a buffer solution of pH 6 containing 1 % 2.3.5-trifenil-tetrazolium salt. Following the protocol, seeds were kept in a dark drying chamber at 23ºC during 24 to 36 hours. Afterwards, the embryo and endosperm coloration was analysed under a binocular at a 25-fold enlargement. Red well-coloured embryos in red endosperm were considered to correspond to viable dormant seeds. Percentages of seed germination and of survival were calculated.

Short-time burial experiment

On 7th July 1999, four seed lots of the same populations but collected in 1999 were buried again. As the year before, samples containing 50 seeds each were buried in fine mesh gauze bags at 2, 8 and 20 cm depth in the same seed free silt-loam soil in Lleida (Spain) next to the other bags. Three replicates of the three populations in each three depths were buried in four individual lots. The samples were exhumed in 15-days intervals in order to study the short-time effect of the burial on *P. rhoeas* dormancy. This experiment will be referred to as short-time burial experiment.

The spare seeds were air dried and kept in a plastic pot in a warehouse under 25ºC. At the second and the fourth exhumation date, three replicates of 50 seeds of each population kept in the warehouse were sown out on the same agar medium but without containing benzimidazole and placed in the growth chamber under the same conditions. Germination was recorded so that loose of dormancy due to burial could be observed.

Temperature was measured with electronic SEAC sensors buried at 5, 10 and 20 cm depth in a nearby grass-covered soil. Data were recorded every day at 7 AM, 13 PM and 18 PM. Daily precipitation was recorded in the same observatory.

Statistical analysis was performed with a standard ANOVA using the SAS system (SAS, 1991). The model used was a split-plot considering the population as the main factor.

The evolution of the monthly mean temperature in all three depths as well as the monthly rainfall is shown in Figure 5.1. Very slight variations in soil temperature were recorded between the three depths. Nevertheless, the shallowest sensor was the one registering the most fluctuations both in the lowest and in the highest temperature ranges.

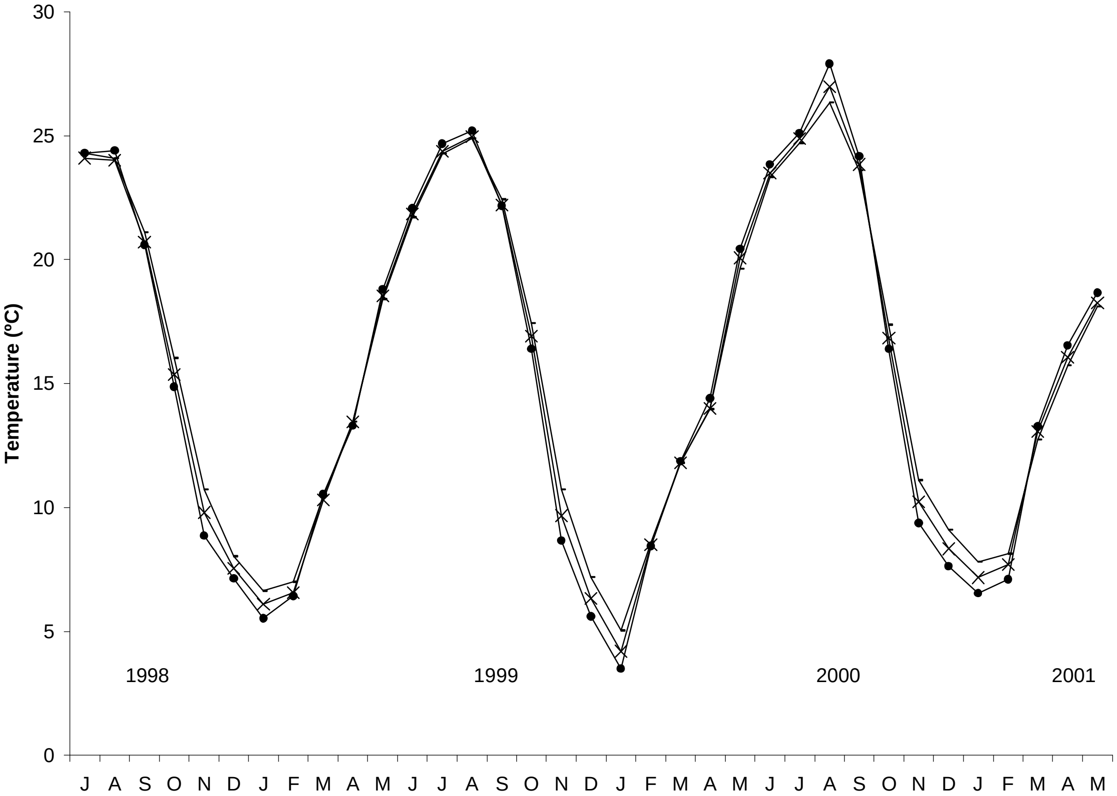


Figure 5.1. a. Climatic data of Lleida (Segrià, Catalonia) during the experiment duration located at 41.63º latitude, 0.597º longitude and 190 m altitude. Monthly mean soil temperatures in ºC at 5 (?), 10 (x) and 20 (-) cm depth.

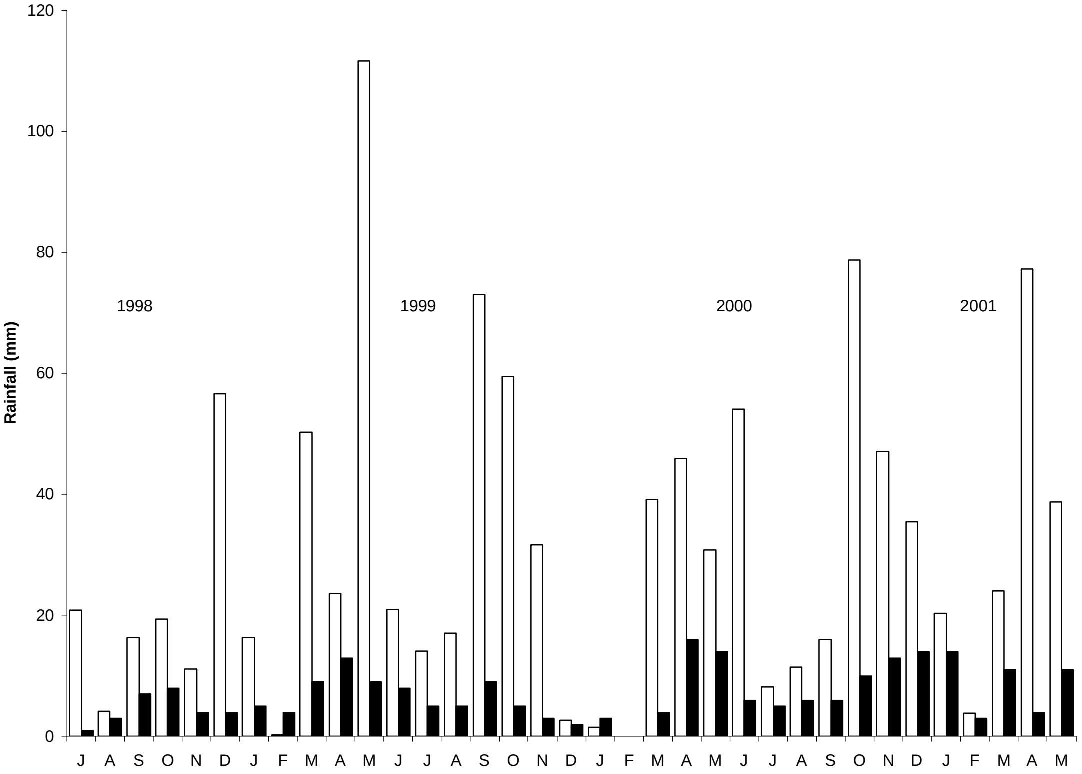


Figure 5.1. b. Climatic data of Lleida (Segrià, Catalonia) during the experiment duration located at 41.63º latitude, 0.597º longitude and 190 m altitude. Mean monthly rainfall in mm (white) and number of monthly rain days (black).

Distribution of rainfall was very different from year to year (Figure 5.1. b). This corresponds to the semi-arid climate of Lleida in which the average rainfall is 365 mm and rain distribution is very irregular and in average concentrated in about 90 days (Meteorological Observatory of Lleida, 2001). The number of days with rainfall was especially low in the winter of 2000.

Results and Discussion

Results of population A/98 buried at 20 cm depth could only be given since January 2000. This is due to the fact that the tissue used for these samples as well as for some others of the same population buried at 8 cm depth, which was different to the rest had completely rotted already 3 months after burial. In all the other cases, most of the seeds out of the 50 seeds placed in each gauze bag could be recovered. Exhumation was sometimes difficult due to very dry or frozen soil.

Long-term burial experiment

The results of the ANOVA analysis are summarised in Table 5.2. Statistically significant differences with P<0.05 were found between populations, between the different depths, between exhumation months and for the interactions of the month with population and depth.

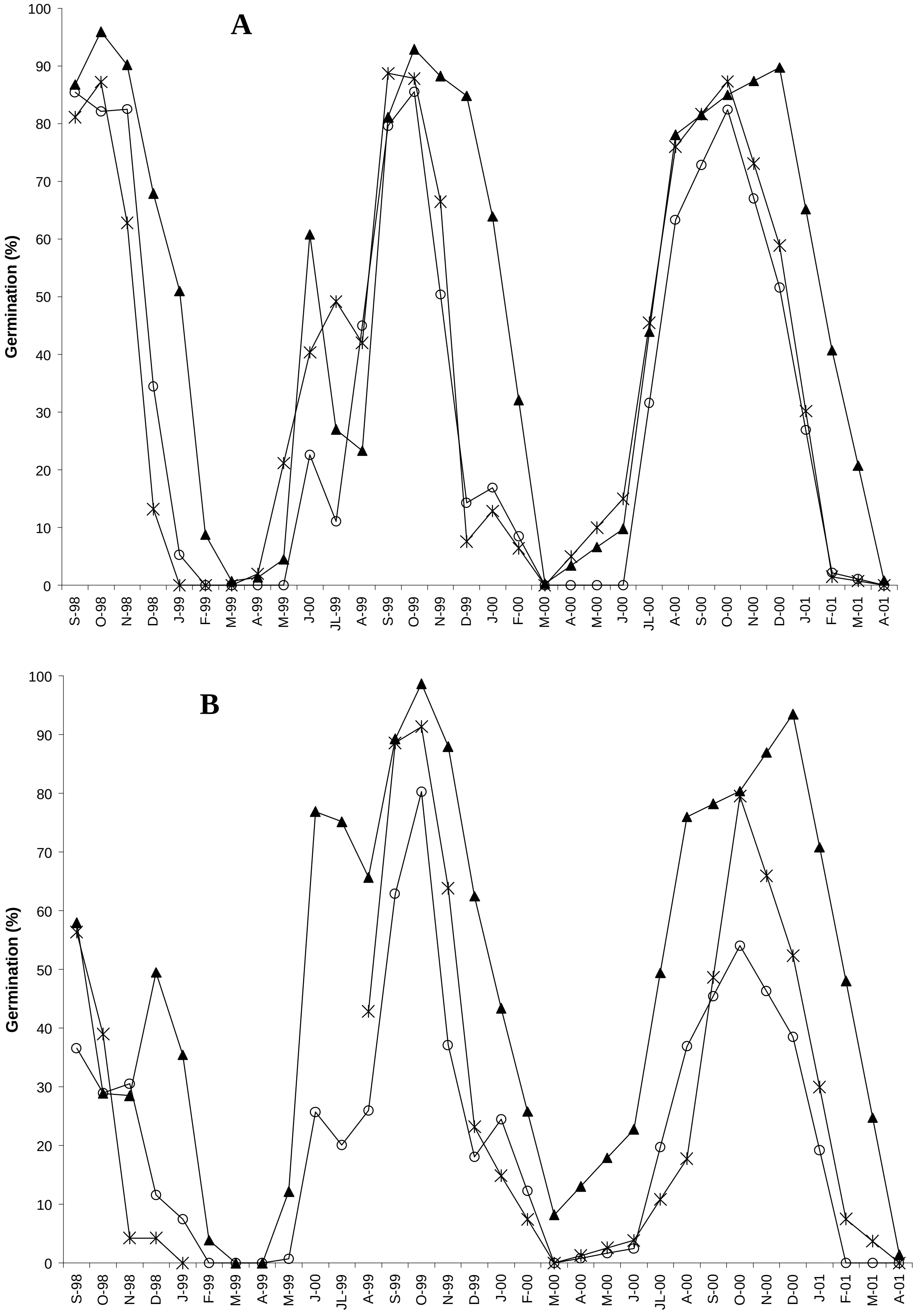
Table 5.2.: Results of the ANOVA of the percentage of *Papaver rhoeas* germination as affected by burial depth, exhumation date and population characteristics.

Source	DF	Mean Square	F	Pr>F
Population	2	3603.2	24.74	0.0388
Block	1	64.6	0.33	0.5687
Block * Population	2	145.6	0.73	0.4809
Depth	2	1166.0	9.64	0.0134
Population * Depth	4	289.6	1.46	0.2142
Block * Population * Depth	6	120.9	0.61	0.7230
Date	23	14547.7	55.8	0.0001
Date * Population	45	993.8	5.0	0.0001
Date * Depth	46	1568.1	7.9	0.0001
Date * Population * Depth	69	260.7	1.3	0.0604

Dormancy evolution in time

The evolution of germination capacity had a strong seasonal influence. The monthly pattern was very similar over the three years of the experiment duration and was constant over the three burial depths (Figure 5.2. a, b, c). The only main difference was that the duration of the spring dormancy was much longer in the first year than in others.

So, germination was high during September, October and November and decreased in December and January. From February to May the dormancy reached closed to 100% and germination increased again from June to September (Figure 5.2. a, b, c). Following the Duncan means separation test, October 1999 and October 2000 were the months with most germination followed by September 1999 and October 1998. February until May 1999, March 2000, June 2000 and April 2001 formed the group of the months with showed clearly the lowest germination rates.



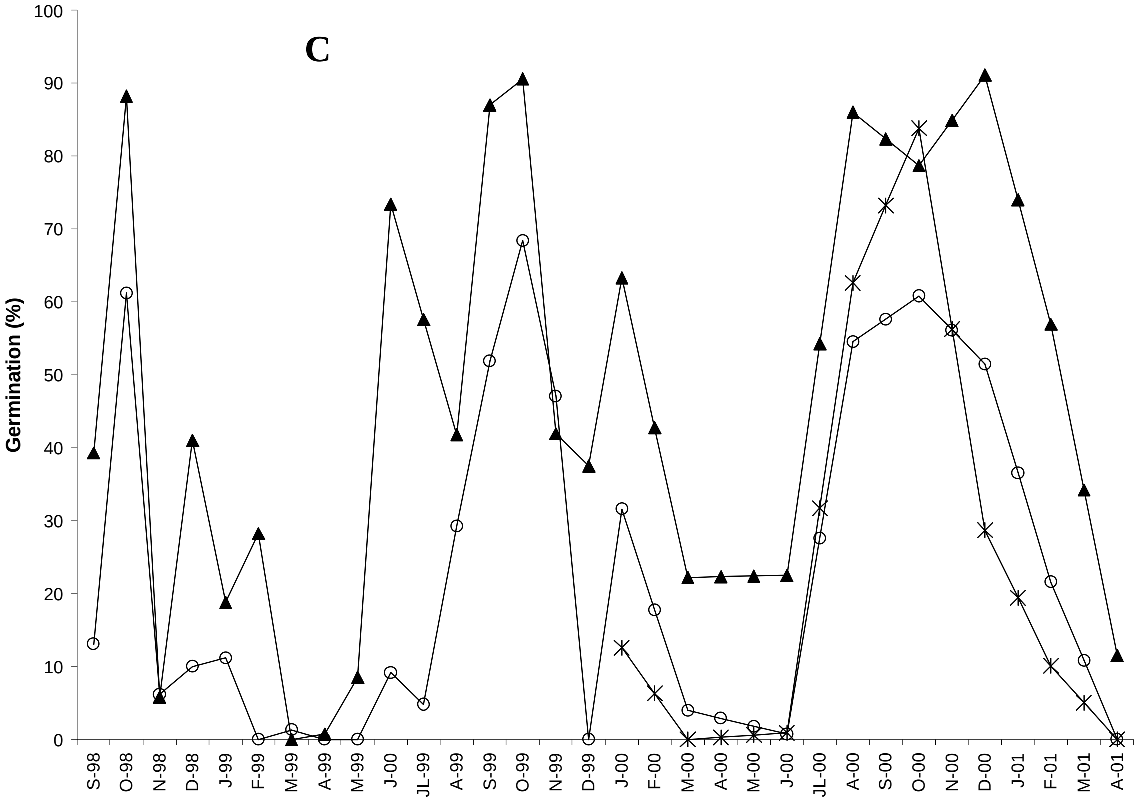


Figure 5.2. Monthly germination (%) of three *Papaver rhoeas* populations buried in July 1998 in a seed-free silt-loam soil. A) Burial in 2 cm depth B) Burial in 8 cm depth C) Burial in 20 cm depth. Population A/98 (**?**); B/98 (?) and S/98 (?).

Influence of burial depth

Germination in the 20 cm depth treatment was more irregular in general terms although the monthly cycle trend was still the same, especially the strong dormancy period during the spring and summer months (Figure 5.2. c). With the exception of some months, germination was highest in the 2 cm layer followed by the 8 cm and finally by the 20 cm layer.

Figure 5.3. represents the interaction between burial month and depth. In general terms, the 2 cm and the 8 cm depth treatments followed both very similar germination cycles and reached even similar germination percentages. Nevertheless, differences between these treatments were observed since burial up to February 1999 (Figure 5.2. a, b, c).

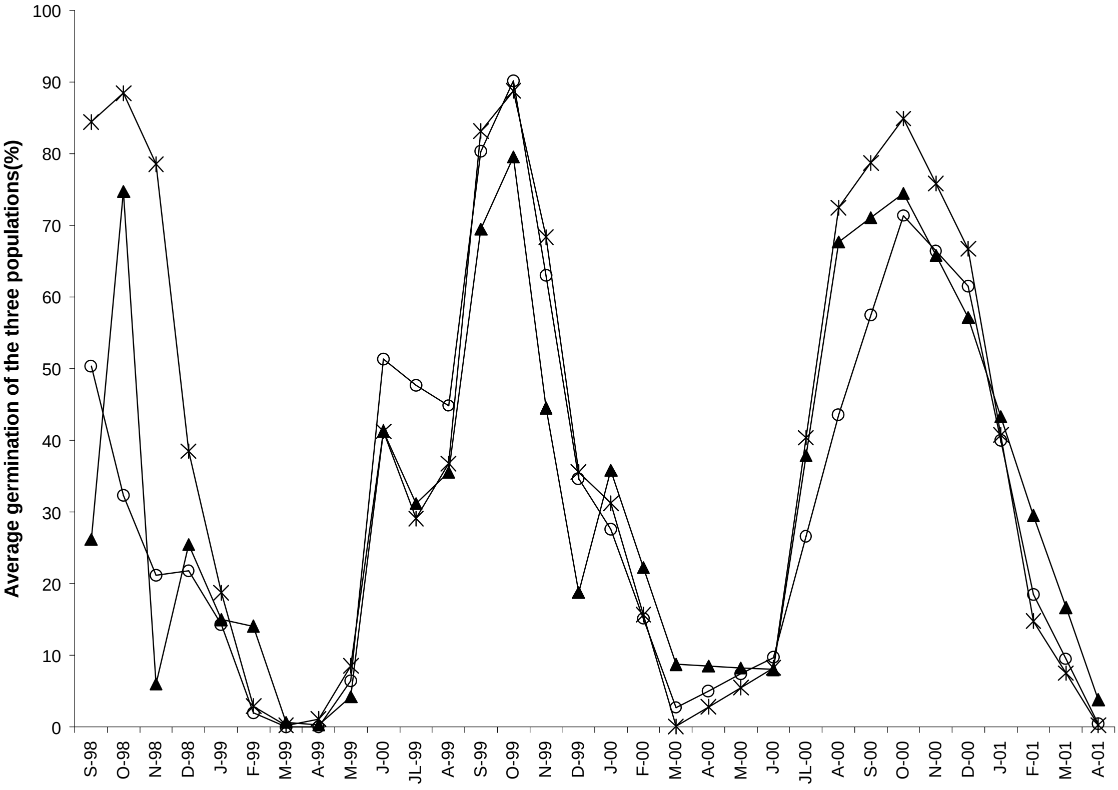


Figure 5.3. Average *Papaver rhoeas* germination (%) buried at 2 (?); 8 (?) and 20 (?) cm depth in July 1998. The interaction month x population was significant in the ANOVA test at P<0.01.

Thus, the influence of the depth on germination for these treatments was mainly important in the first months, only. The shallow-buried seeds lost the primary dormancy very fast so that more than 80% germination was recorded after two months of burial, while in the 8 cm depth treatment the loose of this primary dormancy was slower (Figure 5.2. a, b).

As these data suggest, probably the depth was not an important parameter for the dormancy cycles already after some months. A possible explanation is that regardless of burial depth, seeds received neither light nor air anyway.

Influence of the population

In most of the exhumation dates the S/98 population germinated the most (Figures 5.2. a, b, c and 5.3.), A/98 the second and B/98 the least. The A/98 and B/98 populations, however, behaved in a more similar way in all treatments. Even though, population A/98 generally germinated more than population B/98.

The average germination of each population is showed in Figure 5.4. representing the interaction between the exhumation month and the population. Higher germination did not correspond to bigger seed size of the populations, as A/98 was the heaviest sample followed by S/98 (Table 5.1.). No relation between higher germination and herbicide resistance was found either, as A/98, the susceptible population, behaved very similar to B/98, which was one of the resistant populations.

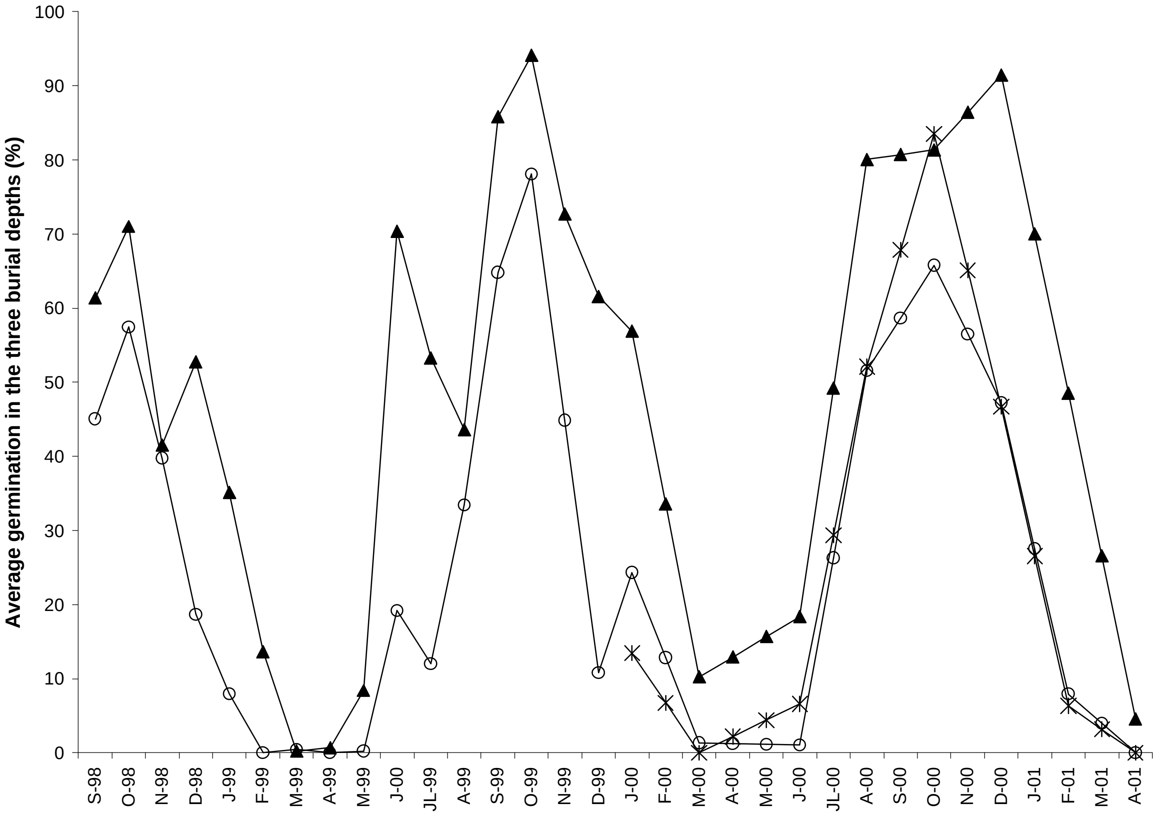
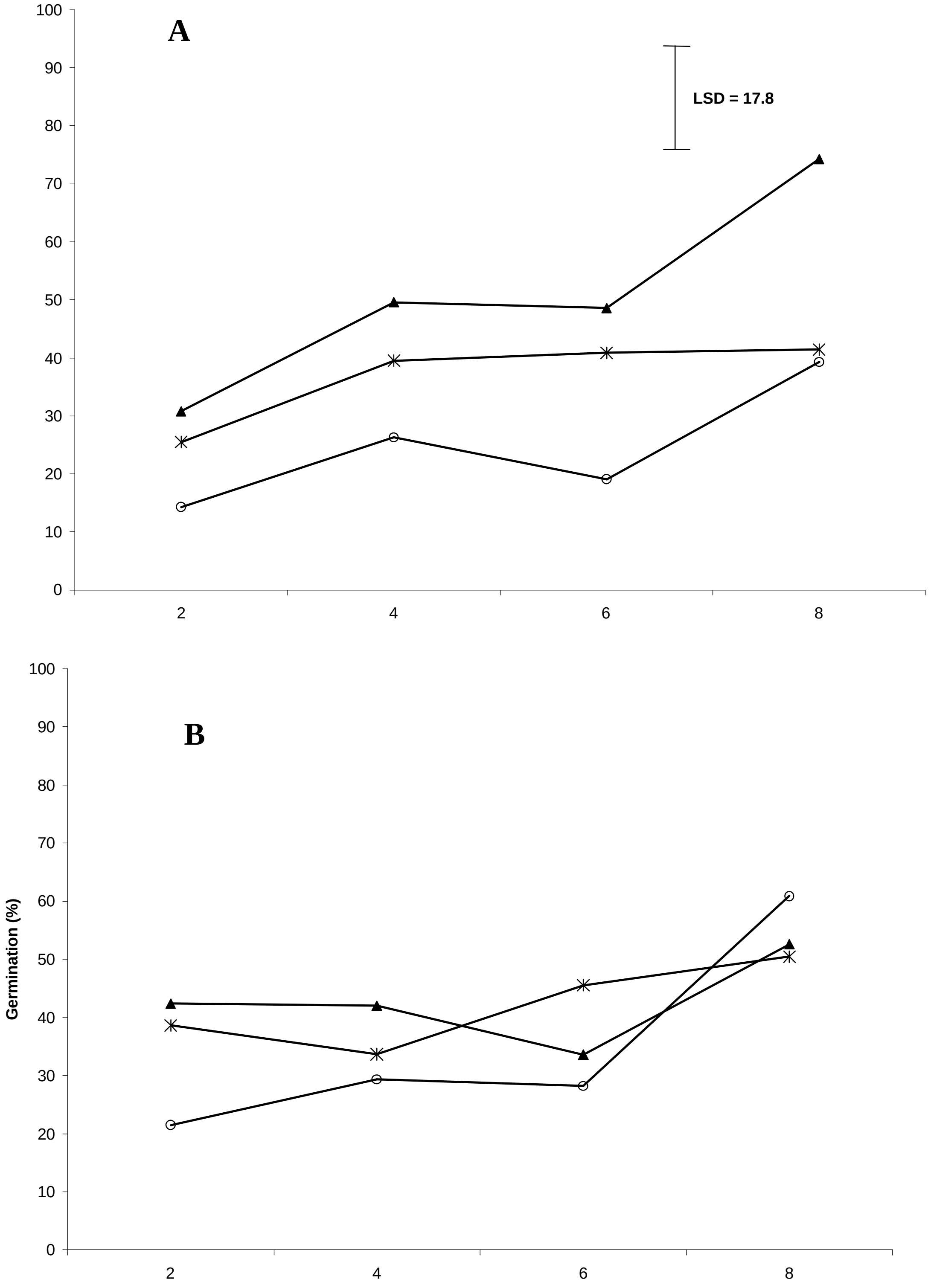


Figure 5.4. Average *Papaver rhoeas* germination (%) of populations A/98 (?); B/98 (?) and S/98 (?) buried at 2, 8 and 20cm depth in July 1998. The interaction month x depth was significant in the ANOVA test at P<0.01.

Short-time burial experiment

The samples were exhumed 16, 29, 44 and 66 days after burial. Germination increased constantly in all four sampling moments and for all three populations (Figure 5.5. a, b, c). The ANOVA analysis revealed that statistical significant differences were detected between populations and between exhumation dates but not between burial depths. Population S/99 germinated the most, A/99 statistically less and B/99 also statistically significant the least (Figure 5.5. a, b, c). The Duncan mean separation test classified the exhumation dates in three separate groups being the two intermediate dates not different from each other. The burial depth was not relevant in any case.


A
LSD = 17.8
100
90
80
70
60
50
40
30
20
10
0
2
4
6
8
B
Germination (%)
100
90
80
70
60
50
40
30
20
10
0
2
4
6
8

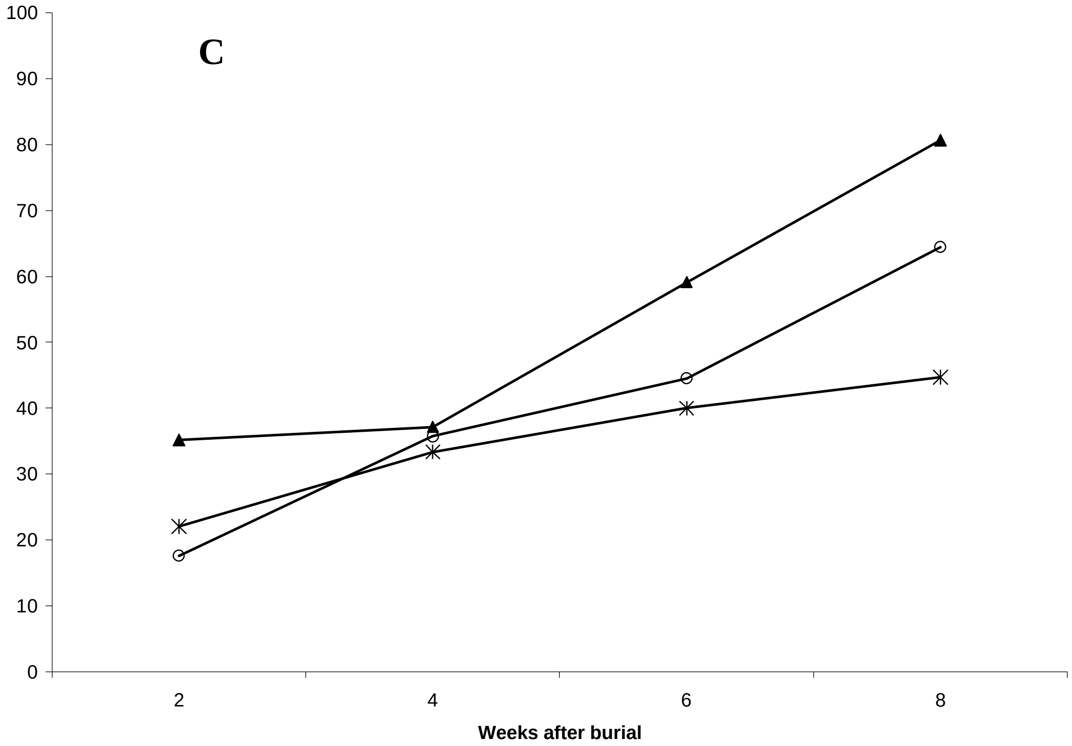


Figure 5.5. Germination (%) of three *Papaver rhoeas* populations A/98 (?); B/98 (?) and S/98 (?) buried in July 1999. Samples were exhumed 2, 4, 6 and 8 weeks after burial. A) Buried in 2 cm depth B) Buried in 8 cm depth C) Buried in 20 cm depth.

Germination of seeds kept in the warehouse

Germination experiments conducted with the same seeds but kept in warehouse revealed that germination was bigger in the buried than in the stored seeds (Table 5.3.). It can be thus supposed that this short-time burial broke primary dormancy of *P. rhoeas*.

Table 5.3. Germination (%) of the three *Papaver rhoeas* populations collected in June 1999 after warehouse storage and after soil burial. For the warehouse stored seeds: mean of germination of three 50 seed lots ± SD. For the buried seeds: mean of germination of three 50 seed lots buried in 2, 8 and 20 cm depth ± SD. DAB = days after burial.

	29 DAB		**66 DAB**	
Population	**Warehouse**	**Buried**	**Warehouse**	**Buried**
A/99	4.0±2.00	17.8±3.60	6.0±3.46	30.6±12.87
B/99	3.3±1.15	28.7±8.75	8.7±1.15	41.1±4.25
S/99	0.0±0.00	36.1±5.86	5.3±2.31	43.9±12.03

These results are consistent with the long-term burial experiment concerning dormancy relief after burial.

Survival

Survival data were calculated out of the sum of germinated seeds and alive seeds identified by the tetrazolium bioassay. In spite of the addition of the fungicide benzimidazole, fungus appeared in the dishes, especially in the freshly buried seeds, in the 20 cm depth treatment and when soil was dry at the exhumation date. This obviously affected the bioassay results, explaining that germination rates in some months were superior to viable seed percentage found in previous months (Table 5.4.).

Table 5.4. Percent of viability of three *Papaver rhoeas* populations buried in July 1998 in 2, 8 and 20 cm depth. Mean of three replicates of 50 initially buried seeds±SD. No A/98 seeds could be recovered from 20 cm depth since January 2000 due to the decomposition of some bags.

Burial depth	Oct98	Jan99	Aug99	Jun00	Feb01
2 cm					
A/98	96.0±4.05	77.5±7.94	98.4±1.34	83.1±4.60	63.4±4.82
B/98	97.0±1.27	80.5±6.90	96.4±3.31	79.4±7.06	77.4±14.25
S/98	98.6±1.19	94.5±1.00	82.5±28.16	81.2±3.30	85.8±5.21
8 cm					
A/98	66.8±14.89	72.7±12.50	72.8±28.85	82.7±3.34	86.1±6.10
B/98	75.9±13.23	84.2±9.38	96.9±0.76	86.0±8.92	89.9±5.31
S/98	59.9±7.78	83.9±1.00	91.8±3.25	63.6±4.91	96.5±3.10
20 cm					
A/98	-	-	-	81.3±8.54	90.7±4.13
B/98	71.6±32.41	52.8±46.24	81.2±19.05	82.5±4.60	85.8±4.35
S/98	94.1±2.45	36.1±27.07	60.9±49.25	82.6±1.07	98.9±1.24

Results were more homogenous within the surface buried seeds and more irregular with increasing depth, as reflected in higher standard deviation. In spite of some variations from month to month the present data show clearly that in all of the tested depths survival of *P. rhoeas* seeds was high after even two and a half years of burial. A very similar behaviour was found for all three populations even if viability tended to be higher for the population S/99. The final tendency was of higher survival rates in increasing depth. This observation is consistent with the finding of Froud-Williams *et al.* (1984) who described that more *P. rhoeas* seeds survived in depth than buried in surface position.

Fatal germination

Loose seed covers were found since April 1999 in the gauze bags. They could clearly be distinguished from rotted seeds and were found mostly in the 2 cm depth treatment. The seed covers corresponded to rests of seeds, which germinated but did not achieve to perforate the gauze bag nor to reach the soil surface. Their appearance was not very regular nor accumulative as expected, but there was always a certain proportion of these seed covers since April 1999 at the 2 cm burial treatment (Table 5.5.).

Table 5.5. Fatal germination (% on total seeds found) detected in the 2 cm deep buried bags containing 50 seeds of *Papaver rhoeas* each. Seeds were buried in July 1998.

	Population		
Month	**2/98**	**18/98**	**48/98**
April 1999	6.7±11.55	18.9±32.79	41.5±34.82
May 1999	0	4.0±6.93	17.3±24.89
June 1999	1.8±3.06	0.7±1.21	0
July 1999	2.0±3.52	1.0±1.79	39.2±27.0
September 1999	18.7±16.20	54.0±43.00	60.8±50.96
October 1999	4.7±6.43	7.7±1.53	28.7±47.1
November 1999	8.3±12.54	2.8±4.91	23.5±40.70
December 1999	26.4±24.59	7.7±13.39	3.0±4.24
January 2000	0	0	6.7±9.87
March 2000	0	15.2±26.27	1.4±2.42
June 2000	0	0	9.0±9.00
August 2000	0	11.0±18.53	13.1±17.77
October 2000	1.4±1.21	0	16.6±20.59
December 2000	6.1±7.13	26.5±26.25	16.8±10.98
February 2001	0	8.2±12.21	9.7±2.41
April 2001	4.2±2.47	3.6±6.24	6.0±3.89

In natural conditions without being placed in a bag, most of the seeds would probably have reached the soil surface. Bishop and Pemberton (1996) tested the influence of depth on the germination capacity of *P. rhoeas* from 0.5 up to 2 cm depth and found out that the weed seeds were able to germinate in all the tested depths. This demonstrates that in the present experiment the recorded fatal germination of the 2 cm deep buried seeds would have probably caused seedlings. Also Froud-Williams *et al.* (1984) state that optimum depth for *P. rhoeas* emergence is between 0.5 and 1 cm depth being 2 cm the maximum emergence depth.

In most of the months the S/98 population had the highest proportion of fatal germination, being consistent with the normally highest germination levels (Fig. 3a). As the affected soil surface of the experiment was small, it was assumed that differences in moisture and temperature conditions were negligible. The irregularity and lack of accumulation from month to month could have diverse explanations. Three replicates of 50 seeds per bag and per population might have not been representative enough for the whole population behaviour. It could also be possible that older seed covers had rotten in the bags and were impossible to be identified afterwards and therefore not classified as fatal germinated seeds.

In the 8 cm and 20 cm treatments, fatal germination was less and even more irregular in the exhumed bags, so that no seed covers were found in many months. The maximum value was 4.8% in July 1999 for the B/98 population in the 8 cm treatment and 10.4% germination in October 1999 for the same population in the 20 cm treatment.

Gerowitt and Scharlemann-Busse (1999) observed a very high proportion of fatal germination in *Galium aparine* after subjecting seeds to inversion tillage burying the seeds in 20-30 cm depth. In this case, ploughing could enhance fatal germination preventing a severe build-up of the seed bank.

In the case of *P. rhoeas*, this fatal germination occurred mainly in upper layers and to a small amount in the 20 cm depth treatment, so that ploughing would probably have little influence on the seed bank reduction due to fatal germination.

Conclusions

When buried, *P. rhoeas* seeds showed a cyclic dormancy pattern, which was very similar in 2, 8 and 20 cm soil depth. Differences between depths were mainly detected in the first months after burial. Germination was high from September to January and very low from February to May, approximately. Thus, if germination wants to be stimulated in order to deplete the soil seed-bank, germination promoting soil disturbance should take place during the late summer since early winter.

Seed viability was still very high ranging between 63 and 99% depending on the burial depth and on the population 31 months after burial. Placing *P. rhoeas* seeds in depth by deep cultivation or ploughing should thus be conducted not very frequently as viable seeds would be moved upwards again and would germinate.

Some differences in behaviour were observed between populations. Nevertheless, one of the resistant populations had a very similar behaviour to the susceptible one. The differences were thus probably caused by the origin of the populations and not by the susceptibility or resistance towards herbicides.

Because of this, no difference in management should be planned if cultural control of a susceptible or a herbicide resistant *P. rhoeas* population is targeted.

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Part B 2

Control methods and strategies

Chapter 6

Ploughing and harrowing effect on a herbicide resistant *Papaver rhoeas* L. population in North-eastern Spain (Catalonia)

Plowing and Harrowing Effect on a Herbicide Resistant Corn Poppy (*Papaver rhoeas*) Population in North-eastern Spain (Catalonia)

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Summary

A field trial on winter barley was established in North-eastern Spain during the cropping seasons 1998-99, 1999-00 and 2000-01. A very high tribenuron-methyl and 2.4-D resistant *Papaver rhoeas* L. infestation had been established in the field.

After decades of minimum tillage, ploughing was conducted in winter 1998 and in winter 2000 in part of the field as a preventive weed control strategy. Also the combination of ploughing in both 1998 and 2000 was tested. Plant density assessments and quantification of the seed bank at the end of the three years were taken.

Less *P. rhoeas* emerged in the ploughed plots and the effect was still visible 2 years after. In the two times ploughed plots, emergence was higher than in the single ploughed plots but lower than in the non-ploughed treatment. Thus, after ploughing two times, still viable seeds were placed again in optimal germination conditions.

Harrowing was conducted as an annual control method in part of the plots. A remarkable reduction of the weed population was observed in all three years after a single post-emergence harrowing regardless of the very different moisture conditions of the soil each year.

At the end of two of the three cropping cycles the harrowing effect was similar to the ploughing, in one year the harrowing was more important. One time, this reduction was also still visible in the following cropping season. The combination of one time ploughing and harrowing gave the biggest weed plant reductions.

Soil cores up to 20 cm depth were taken and the seed bank of the different treatments determined. A similar *P. rhoeas* seed distribution in depth was found for all the different treatments, even if in the recently ploughed plots more seeds tended to be placed in deeper layers. A slight reduction of the seed bank after harrowing two years was detected in some cases.

No clear differences in seed bank between ploughing treatments suggest that no important seed mortality was detected after two years of *P. rhoeas* seed burial in 20 cm depth. The lack of significant differences of the seed bank between harrowed and non-harrowed plots was probably due to the moderate efficacy of this control method, which did not have a big influence on the seed bank.

Occasional ploughing was found to be an effective method for placing *P. rhoeas* seeds in non-optimal germination situations. When the initial weed seed bank was very high as in this field trial, the reduction achieved by ploughing was not sufficient and an additional weed control method should be conducted.

Keywords: *Papaver rhoeas* L., herbicide resistance, mouldboard plough, harrow, seed bank.

Introduction

A rapid increase in herbicide resistance has been observed in North-eastern Spain in the last years in *Lolium rigidum* and in *Papaver rhoeas* L. (Taberner, unpublished data). This situation forces to search for new control strategies. In the case of *P. rhoeas*, herbicide resistant weed populations are often very big, so that even chemical control with other different herbicides is difficult to be effective enough. Because of this, it is necessary to integrate different weed control strategies.

Since cereal price is low and input costs are important, soil seedbed preparation has been replaced by minimum tillage in the study area. In the 60's it was still normal to plough but single or two times cultivation a year in approximately 10 cm depth is the most frequently performed tillage system nowadays. In the chosen field, minimum tillage had been practiced at least in the last 20 years and *P. rhoeas* herbicide resistance to 2.4-D and to tribenuron-methyl had led to a very high almost monospecific *P. rhoeas* weed infestation.

Following Bhowmik (1997) in a field in which no changes in the cropping system had been made during decades, a radical change in soil tillage would bury seeds changing probably the weed population dynamics as the position of weed seeds in soil is likely to influence their population dynamics.

Bishop and Pemberton (1996) analysed the influence of depth on the germination capacity of *P. rhoeas* from 0.5 up to 2 cm depth and found that the weed seeds were able to germinate in all the tested depths. On the other hand, maximum depth of *P. rhoeas* emergence was found to be 2 cm depth (Froud-Williams *et al*., 1984). Because of this, it is supposed that no germination could occur from at least 10-20 cm depth after ploughing.

This burial strategy has been effectively tested in wild oats. After reviewing different tillage experiments in wild oats, Thill *et al*. (1994) concluded that occasional deep ploughing as once every 4 years could reduce populations of wild oats. If ploughing was conducted every year, wild oat populations increased because buried seeds were brought to surface.

Boutsalis & Powles (1998) tested the germination evolution of *Sisymbrium orientale* seeds of resistant and susceptible populations to a sulfonylurea herbicide. A short seed-bank longevity was described for this species, so that in this case seed burial would probably be useful for population reduction if new seed rain was prevented at the same time.

To test this strategy, effective in other weed species, with *P. rhoeas* was one of the aims of this study. A similar experimental design was conducted by McCloskey *et al*. (1991) who, in spite of a very low *P. rhoeas* density, describe that ploughing controlled effectively this weed species.

An additional post-emergence weed control method may be necessary to be combined with the preventive ploughing strategy. In the present study, the effect of ploughing combined with harrowing was tested on a *P. rhoeas* population resistant to tribenuron-methyl and to 2.4-D. Before the appearance of herbicides, a kind of tine weed harrow was used in cereal crops in this part of North-eastern Spain. The existing present commercial types, nevertheless, are completely unknown by farmers of the study area.

The objectives of this experiment were to study on one hand the effect of ploughing on the emergence, depth distribution and survival of *P. rhoeas* and on the other hand the combined effect of ploughing and harrowing on the weed control. Related to the first sub-objective, different treatments were tested. Referring to the second sub-objective a single post-emergence harrowing treatment was conducted.

Material and methods

Field design

The field trial was located on a sandy-loam soil in Baldomar (La Noguera region, Lleida province in Catalonia). The plots measured 5 m x 4 m and were arranged in a split-block design with three replicates and three blocks. The variables were ploughing and post-emergence harrowing and different combinations of ploughing in time (no ploughing, 1998 only, 2000 only and 1998 and 2000).

One single ploughing in autumn 1998 or autumn 2000 allowed to compare the emergence and distribution of *P. rhoeas* influenced by the year of treatment. Ploughing in both years 1998 and 2000 was performed to observe the seed distribution in the soil and the weed emergence after stopping to plough one year only. A two-furrow reversible plough was used.

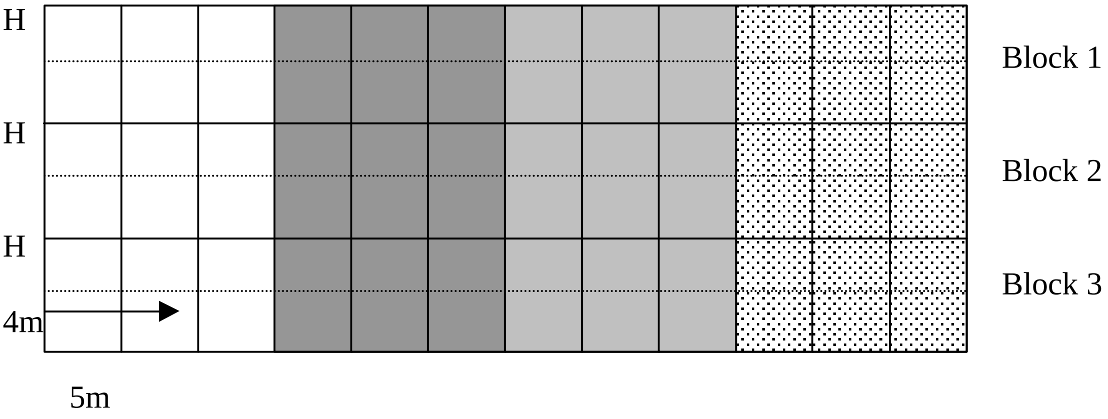

Figure 6.1. Experimental design of the cultural and mechanical weed control trial on *Papaver rhoeas* in Baldomar (North-eastern Spain). □ : No ploughing. ▒ : Ploughing in 1998 only. ░ : Ploughing in 2000 only. ▓: Ploughing in 1998 and in 2000. In each block, harrowing was done in the upper half of each plot across the ploughing treatments corresponding to H. The arrow indicates the sowing and harrowing direction.

The harrowing was conducted every year in the same sub-plots in order to observe both the annual and the long-term effect of this control method. A tine harrow trade mark Einböck with three independent 1.5 m wide sections was used. Wheel level and tine angles were adjusted each time, depending on the soil strength and were maintained in the same position during the whole trial.

As shown in Figure 6.1., ploughing was conducted across sowing direction whilst harrowing was performed following the sowing lines. 8 different ploughing and harrowing combinations resulted from these treatments and 72 sub-plots resulted. The ploughed stripes were placed as grouped as possible in order to avoid surface irregularities inside the trial. Table 1 indicates the dates of each treatment.

Seed emergence evolution and biomass assessment

P. rhoeas plants were counted three times in 0.33 m x 0.33 m frames in each sub-plot several times each year. The first assessment was conducted when the most important emergence flush had finished. This ranged from November to March depending on the year. This way, the effect of the different treatments over more than one cropping season could be observed. Table 6.1. indicates the dates of each assessment.

In the cropping season 1999-00 dry aerial whole plant barley biomass was sampled the 25th May 2000, two weeks before harvest. One sample of each treatment in each block was taken in 0.5 m x 0.5 m frames and weight with a 0.1 g precision balance. Efficacy was calculated following Abbott's formula

[% efficacy = (1-Ta / Ca) * 100]

where Ta is the infestation in the treated plot after treatment and
Ca is the infestation in the treated plot after treatment (Ciba-Geigy, 1992).

Table 6.1.: Sequence of the different treatments and assessments conducted in Baldomar experiment with a herbicide resistant *P. rhoeas* infestation in winter barley. The treatments included harrowing or non-harrowing, non-ploughing, ploughing in 1998, ploughing in 2000 and ploughing both in 1998 and 2000.

Cropping season	**Ploughing date**	**Harrowing date**	**Seedling emergence assessments**	**Other assessments**
1998-1999	26/10/98	24/03/99	23/03/99	
			29/04/99	
1999-2000	-	16/02/00	8/02/00	
			28/02/00	
			18/04/00	
			25/05/00	crop biomass sampling
2000-2001	28/09/00	13/02/01	26/10/00	seed bank soil cores extraction
			09/01/01	
			12/02/01	
			08/03/01	
			30/03/01	

Seed bank characterisation

According to Forcella (1992) the "glasshouse technique" was the chosen sampling system for the seed bank characterization. This method consists in keeping the extracted soil samples moist in the greenhouse during a certain period of time and recording the weed emergence. This author suggested that the glasshouse technique allowed a better correlation with field seedling densities than other methods.

Plastic soil cores of 4.5 cm diameter and 20 cm deep were collected the 26th October 2000 after seedbed preparation. The harrowed stripes were sampled separately from the untreated stripes resulting 72 sampled sub-plots. Five cores were taken randomly inside the sub-plots corresponding to 1590.4 cm^3 sampled volume.

After collecting, the cores were emptied in aluminium trays and separated in two parts corresponding to the upper 10 cm of cultivated soil and to the lower 10 cm, which was supposed to be influenced by the plough only. The trays were placed in a plastic tunnel under near-natural conditions and kept moist by watering.

After the first germination flush, plants were counted and removed and soil dried. Afterwards soil was stirred and rewatered and plants were counted again. No new emergence was observed after February despite the addition of a gibbereline solution the 6th February 2001 at 0.36×10^{-3} g Ga_3 L^{-1}, a concentration found effective in previous experiments.

Climatic data

The monthly average temperatures and rainfall of Vilanova de Meià, the nearest meteorological station are shown in Figure 6.2. During fall 1998 enough rainfall was recorded allowing a humid ploughing and sowing in November. December was so dry that crop emergence was very irregular and weed emergence very late. Harrowing in March could be conducted in appropriate moisture conditions.

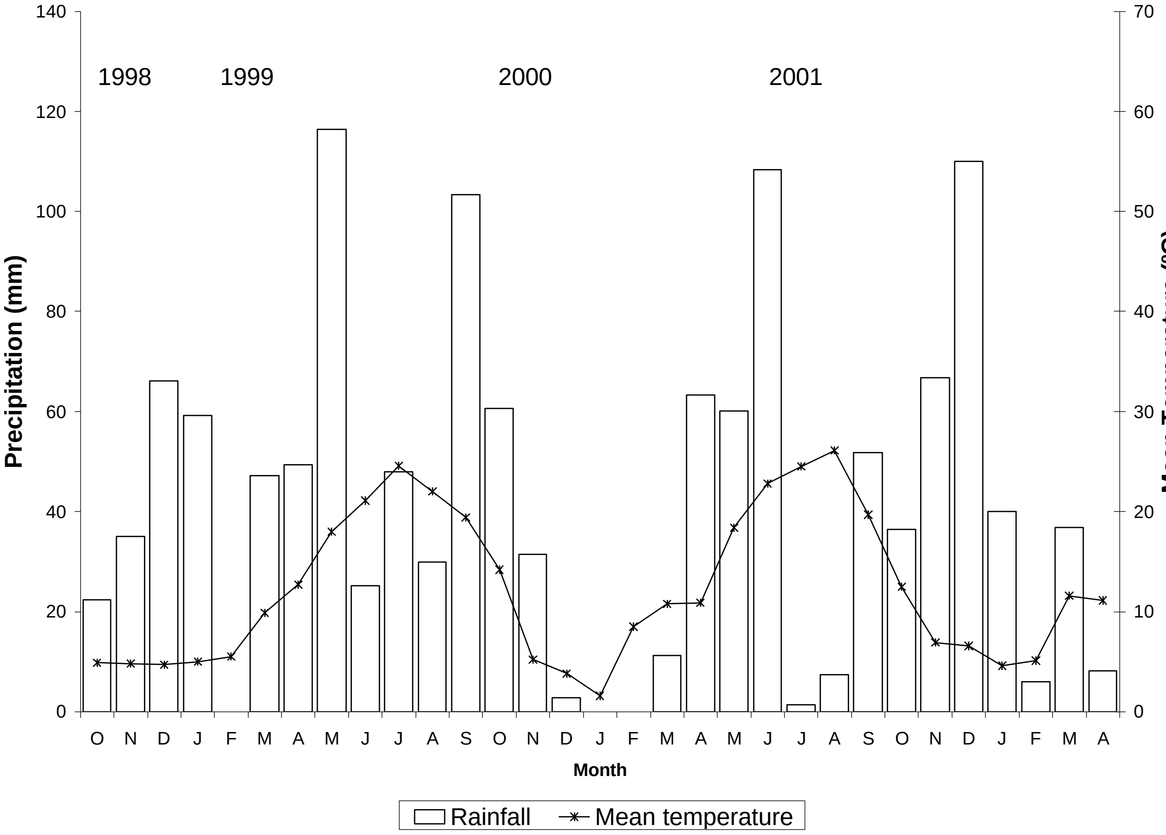

Figure 6.2. Climatic data of Baldomar (La Noguera, Catalonia) during the duration of the experiment representing ? monthly mean temperature and ? monthly rainfall. Data from the nearby observatory in Vilanova de Meià located at 41.991º latitude, 1.022º longitude and 590 m altitude.

The cropping season 1999-00 was characterised by a long drought period from December to end of March. Sowing was conducted in dry conditions waiting for autumn and winter rains. Nevertheless, the late autumn rains allowed higher weed emergence than in the previous cropping season. However, crop and weed establishment was again very irregular. Harrowing in February was conducted on a dry soil.

In 2000-01, ploughing was done in October under good soil humidity conditions. Autumn and winter rain guaranteed an early and a regular crop and weed emergence and establishment. It was difficult to conduct harrowing at the beginning of February due to continuous moisture, which delayed the timing.

General data shows that 2000-01 was the cropping season with more rainy days and with the most humid winter. 1998-99 and 1999-00 were both very dry seasons.

Standard ANOVA were performed using the SAS system (SAS Institute, 1991) with $p<0.05$. Previously ln(x) transformed data on weed density were subjected to an additional contrast analysis.

Results and Discussion

Weed emergence evolution

Figure 6.3. a shows the *P. rhoeas* evolution throughout the three cropping seasons for the unploughed plots and for the plots ploughed in 1998.

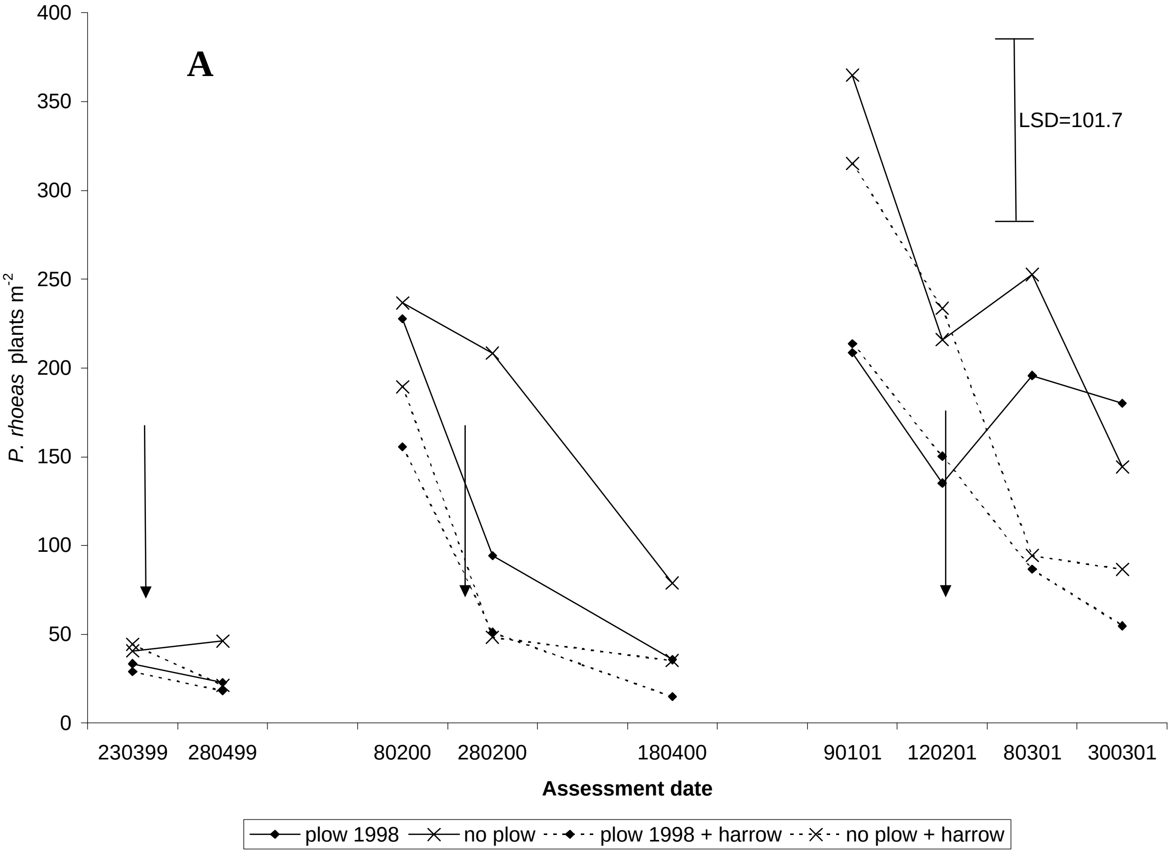

Figure 6.3. a. *Papaver rhoeas* plant number evolution in time studying the influence of ploughing and harrowing on weed emergence. The arrow refers to the harrowing moment conducted in winter 1999, 2000 and 2001. Evolution over the three cropping seasons 1998-99, 1999-00 and 2000-01 of the treatments ploughing in autumn 1998, ploughing in autumn 1998 and harrowing, no ploughing and no ploughing and harrowing. The bar indicates the LSD.

Regardless from the ploughing and harrowing treatments, general *P. rhoeas* density was higher in the cropping season 1999-00 and 2000-01 than in 1998-99 (Figure 6.3. a). In 1998-99, germination was recorded only since March because emergence was very little before, starting in late February. In 1999-00, *P. rhoeas* plants started to germinate in February, as the early winter was very dry.

In 2001, plants already started to germinate in November. In both cropping seasons 1999-00 and 2000-01, maximum germination values recorded in February were similar. Climatic conditions enhanced the cropping cycle in 2000-01 so that the final count was done earlier.

High natural plant mortality was detected in 1998-99 and in 1999-00 especially between February and March. Seedling emergence was recorded since April in the first two cropping seasons and since early March in the cropping season 2000-01. Final *P. rhoeas* density ranged between 46 and 144 plants m^{-2} in the non-harrowed and non-ploughed plots (Figure 6.3. a).

Ploughing effect

Ploughing conducted in 1998 reduced weed density. In spite of this, in very few assessment timings significant differences were found towards the non-ploughed plots (Figure 3a). The differences were generally bigger at the beginning of each cropping season as harrowing was afterwards a more influent parameter. Even if at the end of the cropping season 1999-00 little differences between ploughed and unploughed plots were recorded any more, in winter 2001 there were again higher differences.

Thus, the reduction of *P. rhoeas* emergence caused by the ploughing conducted in winter 1998 was still visible two years later. The contrast analysis at the end of the three cropping cycle taking into account the last counts of each cropping season only, confirms that ploughing in 1998 reduced weed density (Table 6.2.). Data represented in Figure 6.3. a shows how the ploughing effect diminished in time in 2001 probably due to the natural mortality in all the plots including the untreated ones. However, in 1999 and in 2000 the ploughing efficacy increased in time.

As the climatic conditions were more favourable for *P. rhoeas* emergence in the cropping seasons 1999-00 and 2000-01, differences between ploughed and non-ploughed plots were also bigger in these later cropping seasons. *P. rhoeas* seed rain was not prevented from year to year and as both initial and final populations were big, an increase in the soil seed bank occurred. In spite of this, the effect of ploughing in 1998 continued visible. Thus, ploughing had probably buried more seeds than seeds were introduced in the upper soil layer during the following two cropping seasons by the seed rain of the surviving *P. rhoeas* plants.

Table 6.2.: Contrast analysis for the overall behaviour of the different ploughing and harrowing treatments of the last counts over the three cropping seasons 1998-99, 1999-00 and 2000-01 and for the last two assessments of the cropping season 2000-01. Data on *Papaver rhoeas* density of each year were ln (x) transformed for analysis.

Parameter	**Last assessments of the three cropping seasons**		**Last two assessments of the cropping season 2000-01**	
	Estimate	**Pr>|T|**	**Estimate**	**Pr>|T|**
Untreated vs any weed control strategy	-4.18	<0.001	-4.04	<0.001
Untreated vs ploughing in 1998	-0.99	<0.001	-0.33	0.075
Untreated vs ploughing in 2000	-0.35	0.113	-0.85	<0.001
Untreated vs ploughing in 1998 and 2000	-0.12	0.594	-0.17	0.344
Ploughing in 1998 vs ploughing in 2000	0.64	<0.001	-0.51	0.010
Ploughing in 1998 vs ploughing in 1998 and 2000	-0.88	<0.001	-0.16	0.362
Ploughing in 2000 vs ploughing in 1998 and 2000	-0.24	0.28	-0.68	<0.001
Ploughing 1 year only vs ploughing 2 years	-1.11	<0.001	-0.84	0.014
No ploughing vs ploughing of any kind	-1.45	<0.001	-1.35	<0.001
Harrowing vs no harrowing	-3.61	<0.001	-4.24	<0.001
Harrowing vs no harrowing in non-ploughed plots	-0.68	<0.001	-0.67	<0.001
Harrowing vs no harrowing in 1998	0.89	<0.001	1.21	<0.001
Harrowing vs no harrowing in 2000	0.81	<0.001	1.01	<0.001
Harrowing vs no harrowing in 1998+2000	-1.22	<0.001	-1.34	<0.001
Harrowing x ploughing 1 year only	0.08	0.720	0.21	0.253
Harrowing x ploughing 1 or 2 years	0.74	0.058	0.47	0.143
Harrowing vs ploughing or no ploughing	-0.88	0.104	-1.54	<0.001

Statistically significant differences were found between the different ploughing treatments during the cropping season 2000-01 (Figure 6.3. b).

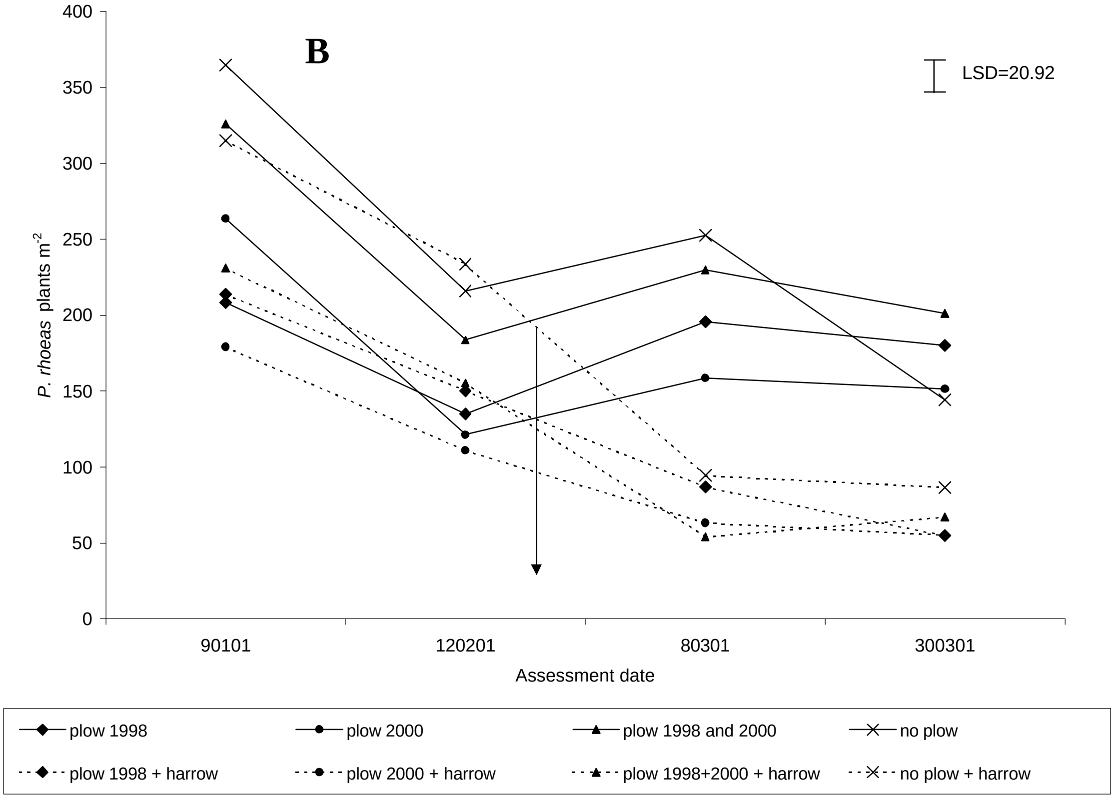

Figure 6.3. b. *Papaver rhoeas* plant number evolution in time studying the influence of ploughing and harrowing on weed emergence. The arrow refers to the harrowing moment conducted in winter 1999, 2000 and 2001. Evolution in year 2001 of the treatments ploughing in autumn 1998, in autumn 2000 or both times combined with and without harrowing each year.

Most weed emergence was recorded in the non-ploughed and the two-times ploughed plots. The lowest *P. rhoeas* density was observed in the plots ploughed in winter 2000 as well as in the plots ploughed in 1998. So, different from ploughing one time only either in 1998 or in 2000, ploughing two times did not contribute in reducing *P. rhoeas* density. This was also confirmed with the contrast analysis (Table 6.2.) both considering the overall behaviour between the three years or only during the last cropping season.

The behaviour in the two-times ploughed plots corresponds to a reduction of the seed bank caused by burial mixed with an increase of *P. rhoeas* seed germination of the exhumed seeds previously buried in 1998, which were still viable and which germinated. These seeds moved upwards after having been buried by ploughing and were probably relieved from their secondary dormancy.

This hypothesis is supported by the observations made by McNaughton & Harper (1964) who describe that dense populations of *P. rhoeas* appear sometimes a first year after ploughing old grassland arising from long buried seeds. Holm *et al*. (1997) also comment that pastures that have not been disturbed for years may become a field full of *P. rhoeas* plants when tilled. This suggests both that seeds maintain viable under buried conditions and that the movement upwards relieves the dormancy. It has also been observed that a high percentage of *P. rhoeas* seeds may survive in 20 cm depth in the climatic conditions of North-eastern Spain at least during 3 years (non-published data).

Plants emerging in the freshly ploughed plots germinated faster than the others (data not shown). This is maybe an explanation for the initial higher emergence in the plots ploughed in 2000 compared with the plots ploughed in 1998 (Figure 6.3. b). Thus, as concluded for wild oats by Thill *et al.* (1994), only occasional deep ploughing would probably be interesting for *P. rhoeas* management.

Weed density in the plots ploughed in 2000 was the lowest at the end of the cropping cycle 2000-01. If the overall weed density in these plots, which were kept unploughed during the two first cropping seasons and which were ploughed at the beginning of the third one is analysed, no difference towards the untreated and towards the two-times ploughed plots was found (Table 6.2.). If the two last assessments of cropping season 2000-01 were analysed alone, however, ploughing in 2000 caused a even lower weed density than the plots ploughed in 1998 and than the plots ploughed in 1998 and 2000 (Table 6.2.).

Taking advantage of the real reduction of the weed population by ploughing as part of a possible management strategy, it could be targeted to bury the seeds one time only trying to deplete the remaining seed bank by an effective post-emergence control method. This eradication strategy is probably difficult to achieve due to the extreme prolificity of *P. rhoeas*.

Following McNaughton & Harper (1964) under favourable circumstances each *P. rhoeas* plant may bear several hundred large capsules containing more than 1000 seeds each. For herbicide resistant *Alopecurus myosuroides,* Moss (1985) concluded that any eradication policy is unlikely to be effective in a cropping system dominated by cereals due to the sufficient seed survival of that weed. This is probably also valid for *P. rhoeas*.

In extreme high *P. rhoeas* infestations probably either a crop rotation or even fallow will be necessary to reduce the population in a significant way.

Harrowing effect

Post-emergence harrowing was conducted in quite dry conditions in early spring 1999 and in winter 2000. In winter 2001 the rainy winter delayed the treatment as the soil hardly dried out in weeks. In spite of theses differences, harrowing was effective in all cases (Table 6.3.). The contrast analysis described in Table 2 shows that harrowing reduced weed density in a statistically significant way regardless of the year and of the ploughing treatment even if the plots were not ploughed.

Table 6.3.: Percentage of efficacy in the post-emergence harrowing treatment on *Papaver rhoeas* and percentage of mortality in the untreated plots as comparison. Harrowing was conducted as a control method in plots subjected to different ploughing treatments. DAT = days after treatment. Mean of nine replicates of each of the three blocks ± SD.

Harrowing date	**DAT**	**No ploughing**	**Ploughing 1998**	**Ploughing 2000**	**Ploughing 1998 and 2000**	**No treatment**
March 1999	36	44.6±23.41	25.7±32.31	-	-	6.8±24.62
February 2000	12	72.3±32.81	67.7±42.09	-	-	8.7±74.4
	51	81.4±6.23	89.7±7.79	-	-	66.4±10.37
February 2001	23	60.6±5.76	44.2±30.83	49.3±13.74	65.2±13.87	-14.3±13.78
	45	63.9±5.44	60.8±37.82	50.2±2.12	57.4±20.94	33.5±2.86

The lowest efficacy values were obtained for the first cropping season, in which also fewest *P. rhoeas* plants were recorded both before and after harrowing. In the untreated plots, weed emergence was recorded expressed by the negative efficacy values in the first counts of all three years. This demonstrated that the efficacy found in the harrowed plots was due to the treatments and not influenced by natural mortality. Later in the season, higher weed mortality was found in the untreated plots, which explains the efficacy increases in time in the harrowed plots (Table 6.3.).

The efficacy values were in the range of other experimental results. For the same weed species in a similar climatic area, Lezaún *et al.* (2001) obtained between 66 and 91% efficacy on *P. rhoeas* in different locations of Northern Spain with single early post-emergence harrowing. In field experiments conducted in Central Spain on winter cereal an efficacy of 50-75% on *P. rhoeas* was achieved (Moyano *et al*., 1998) after a single harrowing conducted in late post-emergence at the tillering stage of the crop.

In 2000, no new emergence was recorded after harrowing. In 1999 and especially in 2001, *P. rhoeas* germinated in the non-harrowed plots but not in the harrowed plots after the treatment (Figure 6.3. a). Thus, harrowing probably killed the late germinating *P. rhoeas* seedlings starting to germinate and did not favour any new important emergence. This shows that harrowing was probably conducted in the appropriate moment.

Natural weed mortality reduced differences in time. In spite of this, the harrowing effect was also still visible from one cropping season to the other, suggesting seed rain reduction (Figure 6.3. a). This was especially remarkable between the years 1999 and 2000, and could also be observed for the non-ploughed plots between 2000 and 2001.

Combined effect of ploughing and harrowing

In all three cropping seasons the smallest final *P. rhoeas* plant number in the last assessments was found in the plots ploughed in 1998 combined with harrowing (Figure 6.3. a, b). In 2001, harrowing had a much more important effect on the final weed plant number than ploughing alone (Figure 6.3. b). In 1999 and in 2000, the final *P. rhoeas* plant number either after ploughing or after harrowing was the same. Following the contrast analysis showed in Table 6.2., any ploughing and harrowing combination had a clear effect on *P. rhoeas* plant number reduction.

In Figure 6.3. c the mean overall weed density of the three cropping seasons taking into account the final assessments only and the *P. rhoeas* density of the last cropping season taking into account the last two assessments are represented. The Student-Newman-Keuls test classification clearly shows that harrowing was the most effective control method regardless of the ploughing treatment. Ploughing also reduced weed density but in a more irregular way (Figure 6.3. c).

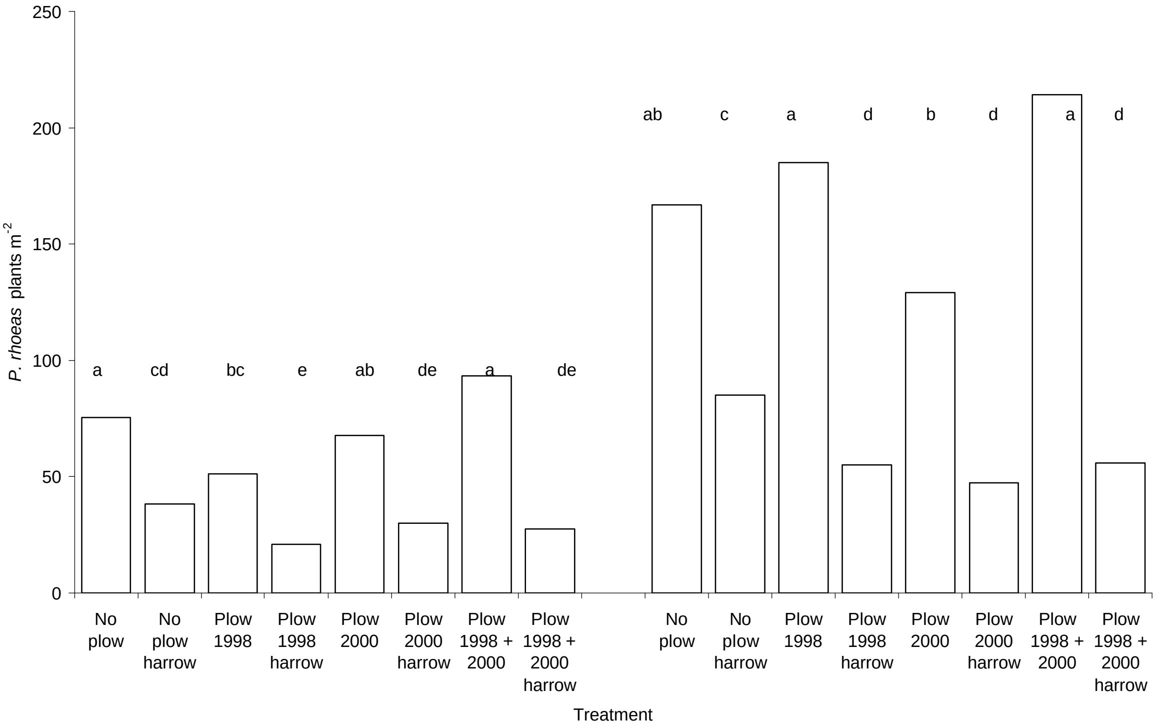

Figure 6.3. c. *Papaver rhoeas* plant number evolution in time studying the influence of ploughing and harrowing on weed emergence. The arrow refers to the harrowing moment conducted in winter 1999, 2000 and 2001. Mean values of the different treatments of the last assessment dates of all three cropping seasons (left) and of the two last assessment dates of the year 2001 (right). Different letters refer to statistically significant differences following the Student-Newman-Keuls test at P<0.05.

Seed bank characterization

Compared to other studies in winter cereal a very high seed bank was found, which achieved up to 18,000 seeds m^{-2} from 0 to 20 cm depth in some treatments. Cavers *et al.* (1992) found up to 7092 total weed seeds m^{-2} from 0 to 15 cm depth in a barley field, Moss (1985) found up to 417 *Alopecurus myosuroides* seeds in 0 to 22.5cm depth in winter cereals.

Data from *P. rhoeas* emergence from 0 to 10 cm depth and 10 to 20 cm depth were submitted to the ANOVA analysis separately with the split-block model used for analysing the *P. rhoeas* density including the depth variable. No statistically significant differences in the seed bank in depth, due to harrowing neither due to ploughing were found. In spite of this, the tendency was: more seeds in the upper layer in the non-ploughed and in the 1998 ploughed plots, the same amount of seeds in the upper and lower layer in the plots ploughed in 2000 and a higher amount of seeds in depth in the two-times ploughed plots (Figure 6.4. a).

The abundant emergence of *P. rhoeas* in 1999 and 2000 and the following seed rain probably enriched the upper part of the seed bank. This way the proportion of buried seeds in the 1998 ploughed plots reduced and the effect of ploughing seemed to have disappeared after two years of ploughing. In the plots ploughed in 2000 or two-times the results indicate that recently buried seeds were placed basically in depth although an important amount of freshly exhumed *P. rhoeas* seeds were found in the upper soil layer.

The total amount of seeds found between 0 and 20 cm depth was biggest for the plots ploughed in 1998 and for the plots ploughed in 1998 and in 2000. In contrast with the non-ploughed plots, in these cases seeds had been placed in upper layers after the burial in 1998. The developing plants had the opportunity of germinating and to produce seeds. Probably the accumulation of these new seeds could have caused the difference.

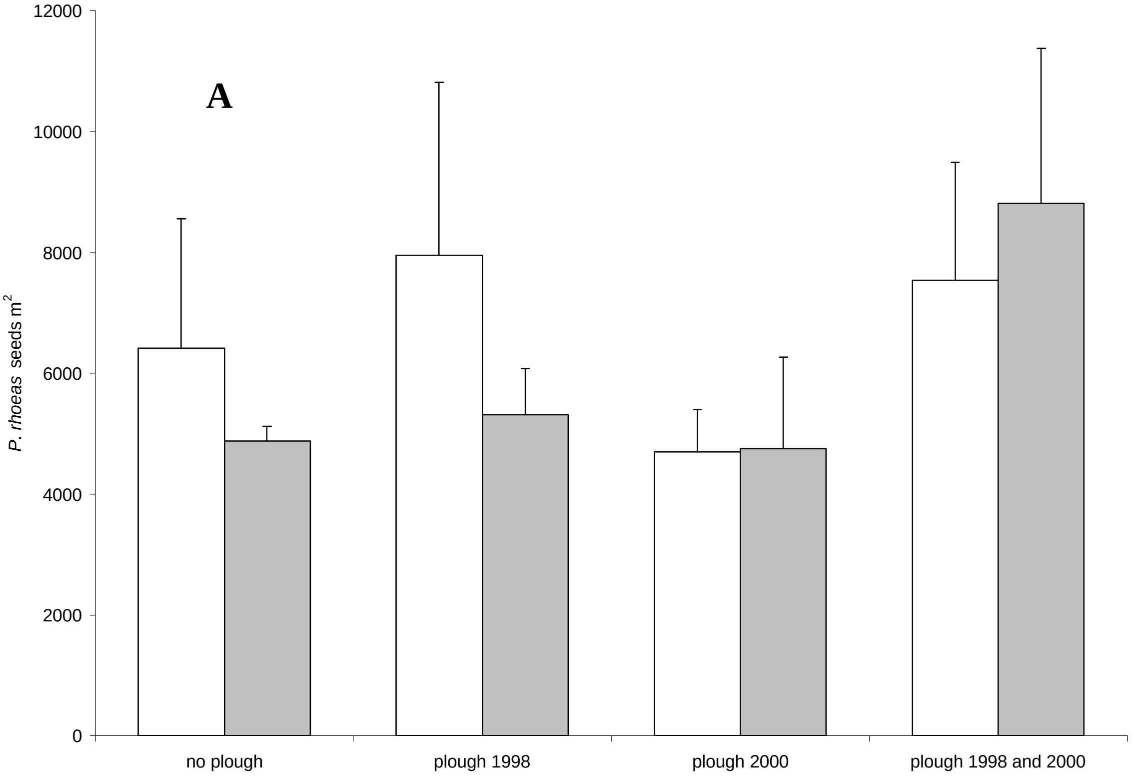

Figure 6.4. a. Emerged *Papaver rhoeas* seedlings per m^2 from the seed bank soil samples taken from 0 to 20 cm depth. The tested treatments were no ploughing, ploughing in autumn 1998, ploughing in autumn 2000 and ploughing both times combined with and without harrowing each year. The lines indicate the LSD. Separated layers from 0 to 10 cm (white) and from 10 to 20 cm (grey).

Due to the lack of significant differences found respective to depth, data of the total soil layer from 0 to 20 cm was analysed for the other variables. Also in this case, no differences between any ploughing or harrowing treatments were statistically significant. The lack of differences between the plots ploughed in 1998 or in 2000 shows that the initial weed seed number in surface was similar both years. In the two-times ploughed plots, however, more seedlings tended to germinate indicating a bigger seed bank (Figure 6.4. b).

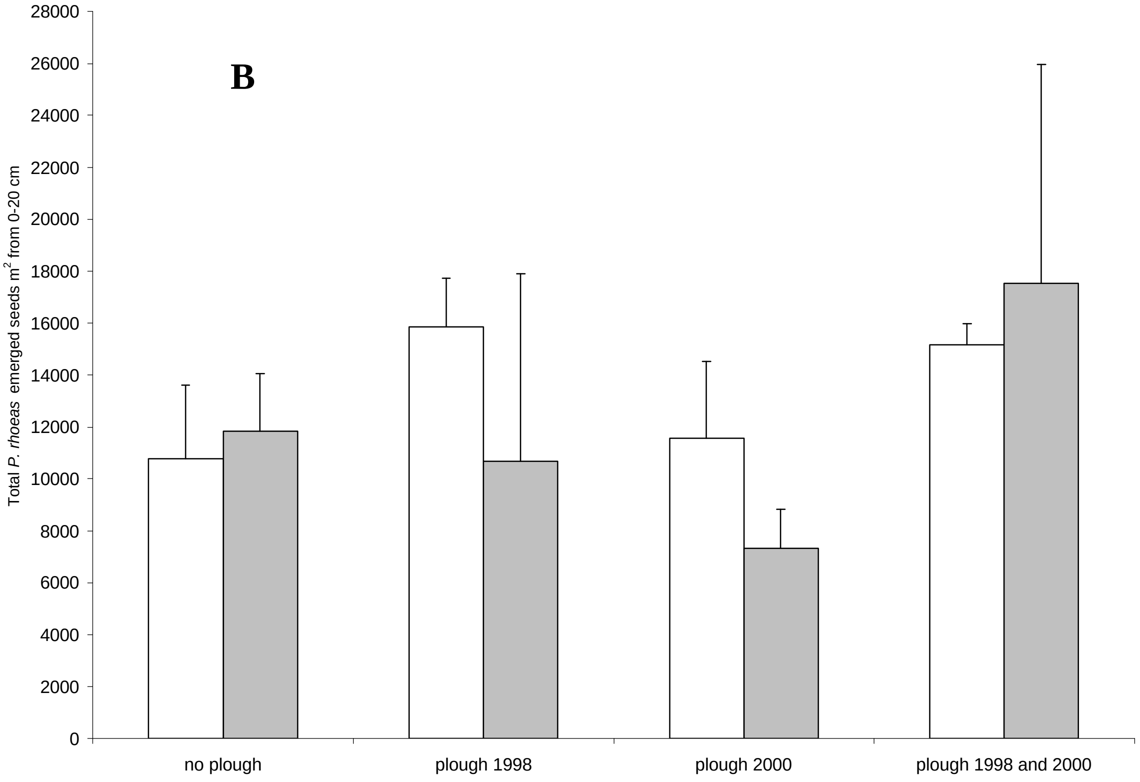

Figure 6.4. b. Emerged *Papaver rhoeas* seedlings per m^2 from the seed bank soil samples taken from 0 to 20 cm depth. The tested treatments were no ploughing, ploughing in autumn 1998, ploughing in autumn 2000 and ploughing both times combined with and without harrowing each year. The lines indicate the LSD. Total emerged seedlings from 0 to 20 cm depth for non-harrowed (white) and for harrowed plots (grey).

This increase could probably be explained as before, suggesting that more seeds had had the opportunity of germinating and of producing new seeds. Another explanation could be the lack of dormancy in these exhumed seeds. This supports the observations of McNaughton and Harper (1964) who suggested that the movement upwards relieved dormancy in *P. rhoeas*.

In the 1998 ploughed plots also a quite high germination was recorded indicating that few seeds had rotted or died in the burial period. This founding is consistent with Barralis *et al*. (1988) who classified *P. rhoeas* as a weed species with a slow decrease of germination capacity in time. In their experiments conducted in France, soil was ploughed every year during 5 seasons and the average germination ratio was much higher the third, fourth and fifth year than the first and second year.

In spite of the huge seed bank, the variability between plots and between samples inside the same plots was probably the cause of data dispersion causing no differences between treatments.

Mohler and Galford (1997) observed in their experiments with *Abutilon theophrasti, Amaranthus retroflexus* and *Chenopodium album* that soil inversion with a mouldboard plough would probably on one hand decrease seed emergence but at the same time increase seed survival of the buried seeds. This would be due to several reasons including reduction of predation and desiccation and by changing the soil in a way that promotes survival. In the present study it could be demonstrated that seed emergence was reduced during at least two years after ploughing.

Referring to the increase in seed survival due to burial, the present data could not support this suggestion although it can at least be said that no important reduction of the *P. rhoeas* seed bank was found due to a two-year burial in 20 cm depth and that seeds were able to germinate after exhumation. This observation is consistent with the results of Kjær (1940) who buried *P. rhoeas* seeds in 25 cm depth during 5 years obtaining still 30% of germination capacity in field conditions after exhumation.

Froud-Williams *et al.* (1984) also found that most *P. rhoeas* seeds survived in 5 cm depth without cultivation compared to surface position and cultivation in a two-years experiment, so that ploughing increased seed survival.

The weed emergence pattern described previously suggests that the ploughing effect was visible during a long period caused by seed burial. Unfortunately, this could not be clearly supported with this seed bank study although survival of seeds in depth could be demonstrated.

Soil samples were taken after two consecutive years of harrowing and immediately after ploughing in 2000. Therefor, the effect of harrowing in the upper soil layer could not be analysed for the recently ploughed plots. In spite of this, a possible decrease of the seed bank could be remarkable in the total soil layer also in the recently ploughed plots. These data are represented in Figure 6.4. b. Harrowing during two years tended to decrease the seed bank in the 1998 or 2000 ploughed plots (Figure 6.4. b). Slight increases of the seed bank in the harrowed plots were observed for the non-ploughed and two-times ploughed plots. Maybe the high seed bank reduced the differences in the other cases. Thus, in spite of its moderate efficacy on weed density, harrowing had in some cases an influence on seed bank reduction.

Plant biomass

No influence in crop dry weight due to the different ploughing and harrowing treatments was detected. Also no statistical significant differences were observed with $P<0.05$ (Figure 6.5.).

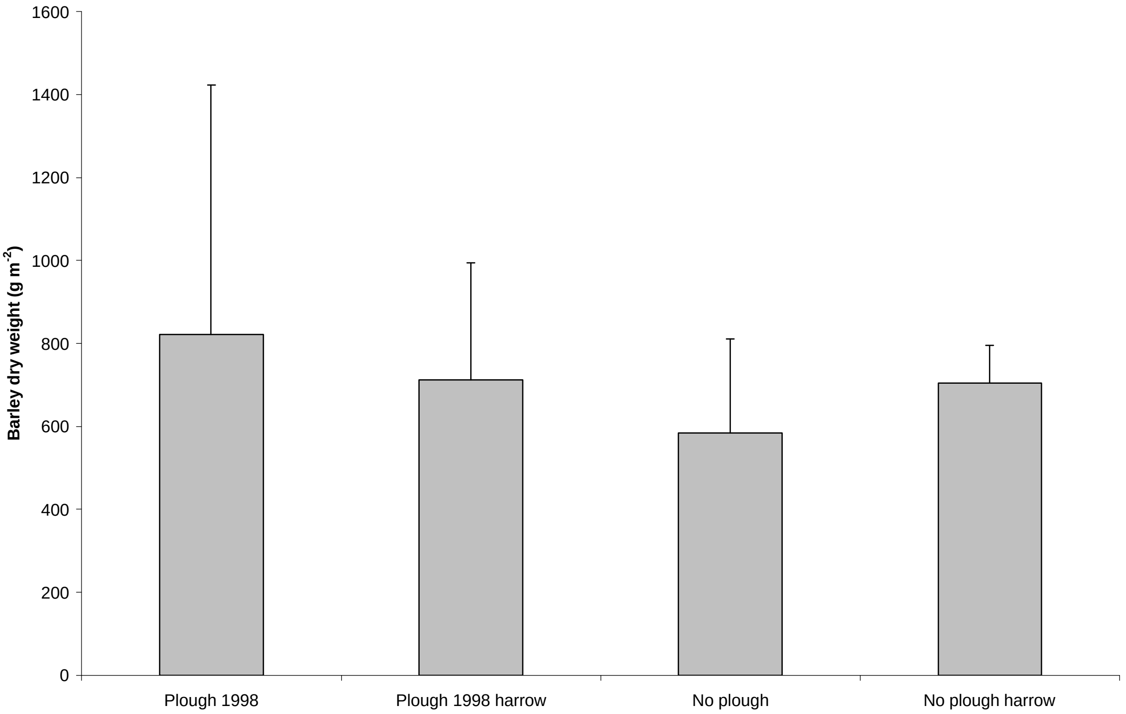

Figure 6.5. Dry aerial barley biomass in g m^{-2} sampled in summer 2000. The lines indicate the SD. The tested treatments were no ploughing, ploughing in autumn 1998 combined with harrowing in winter 1999 and 2000 and with no harrowing.

Conclusions

One-year ploughing reduced *Papaver rhoeas* L. emergence in the field trial, regardless if conducted in 1998 or in 2000. The reduction was around 40%. The effect was still visible two years later.

Ploughing two-times with a one-year period in-between diminished the effect, probably because seeds brought back to surface were able to germinate. Despite this, still some reduction was achieved compared to non-ploughed plots.

Single post-emergence harrowing reduced the weed population considerably even if very different moisture conditions occurred in the different years. In one year, the harrowing effect was more important than the ploughing. The best treatment was the combination of one-year ploughing with harrowing.

No differences in seed distribution in depth nor in the size of the seed-bank were observed in any case.

Ploughing was considered to be an effective method for placing *P. rhoeas* seeds in non-optimal germination situations, which will have to be reinforced by other control methods, when the populations are too big.

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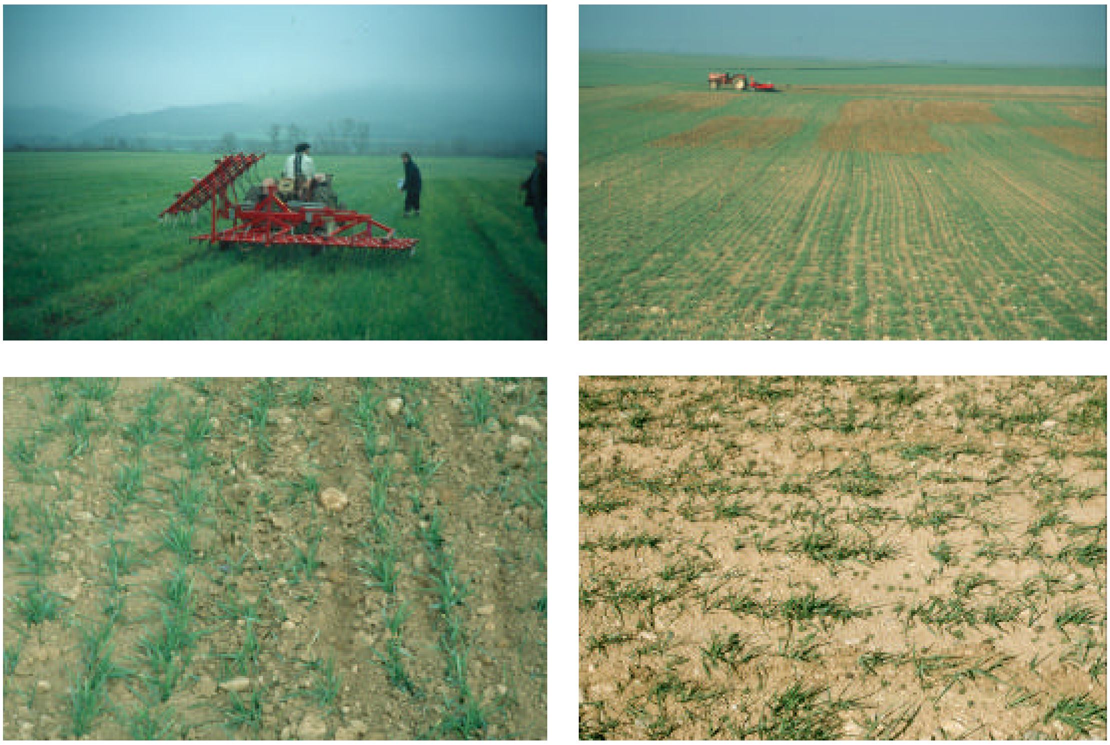


Chapter 7

Mechanical control of herbicide resistant *Papaver rhoeas* L. population in North-eastern Spain (Catalonia)

Summary

The effect of weed harrowing on herbicide resistant *Papaver rhoeas* L. populations was tested in 11 field trials established in North-eastern Spain (Catalonia) on winter cereal during the cropping seasons 1998-99, 1999-00 and 2000-01. Pre-emergence harrowing, early, late and two-times post-emergence harrowing, single and go-and-back passes during the same day, the influence of the roll and of the speed on the efficacy were the analysed treatments. Some of these factors were tested in each trial. Weed density was recorded in all cases and crop and weed biomass was weighed in the trials conducted in 1999-00.

No significant weed control was observed after pre-emergence harrowing.

In post-emergence, *P. rhoeas* plants were much better controlled in early growth stages, which was January and February in the tested conditions. In some cases, one single treatment was enough to reduce the population's density down to acceptable levels. In other cases, two treatments were necessary. Repeating two post-emergence treatments in time improved the efficacy in most of the tested cases.

Conducting a go-and-back pass at the same date compared to single harrowing improved the control in one out of three tested fields and did not lead to a different density in the other two cases.

Less *P. rhoeas* mortality occurred in the rolled non-harrowed plots but similar plant decrease was obtained in the harrowed plots.

Efficacy increase due to increasing speed was found in one out of three locations, only.

The efficacy decreased in time in most of the cases. A high natural mortality in the untreated plots combined with the recovery of plants after harrowing provoked that in many cases weed density in the untreated and in the harrowed plots was very similar at the end of the cropping season. Plant survival was higher in the rolled plots, so that efficacy was also higher.

The climatic conditions after harrowing were found to influence strongly the control effect. Drought enhanced weed mortality; moisture favoured weed re-growth but in one case also the crop growth so much, that crop competition increased the initial weak control. In two field trials the harrowing stimulated new *P. rhoeas* germination.

In the fields where crop biomass assessments were conducted no decreases caused by harrowing were recorded, suggesting that no important crop damage resulted even when go-and-back treatments were conducted at the same day.

The harrowing timing should be decided in each case depending on the specific field and year conditions but January and February would be probably the most indicated months for harrowing in the tested conditions. Further experiments in pre-emergence and in early post-emergence are needed in order to improve its control potential.

Keywords: mechanical weed control, harrow, *Papaver rhoeas* L., pre-emergence, post-emergence, roll.

Introduction

General aspects on mechanical weed control

Mechanical weed control, specifically harrowing has been traditionally conducted in the cereal fields of Catalonia. Since the appearance of herbicides in the 50’s, however, this technique as well as other preventive and cultural weed management practices almost disappeared. Soon afterwards, ecological agriculture has reappeared especially in Northern Europe taking again into account old agricultural practices. As a consequence, also research started focusing on new topics as the mechanical weed control already since the 50’s with some PhD studies like Habel (1954) and Kees, (1962).

In Northern Europe, research on these topics increased during the end of the 80’s. Afterwards, a lot of work has been conducted in Denmark starting with Rasmussen *et al.* and in Sweden with Ascard *et al.*, especially with harrowing techniques and continuing afterwards with other mechanical weed control techniques in row crops. The celebration of the 4th International IFOAM conference held in Dijon (France) in 1993 focused on non-chemical weed control and the foundation of the Mechanical Weed Control Working Group of the European Weed Science Society clearly demonstrates the general interest in these topics.

In Spain, an increase of experiments on weed harrowing was observed at the end of the 90’s (Lacasta *et al.*, 1997, Moyano *et al.*, 1998, Pardo *et al.*, 2001, Zaragoza *et al.*, 1999). Previously, during 1920 and 1960, approximately, Carmelo Benaiges had conducted research on a traditional farmers’ practice grouping the cereal lines, allowing hoeing between the wider rows (Lacasta & Meco, 1996). In Italy, Bárberi *et al*. (2000) and Ferrero & Vidotti (2001) among others also published some first harrowing results in this period of time.

Even if many experiments have been conducted in Northern Europe, there is an important need to collect information about mechanical weed control in the South European conditions. In cereal crops, many parameters differ from the Northern to the Southern conditions. The main factors could be later sowing dates, warmer winters allowing weed and crop growth during longer part of the winter, shorter cropping seasons, stony and dry soils, irregular rainfall, as well as other weed species and weed populations. In Northern conditions it is often difficult to conduct harrowing in autumn or early winter due to soil wetness (Koch 1964a, Wilson *et al.*, 1993). Weeds germinating in this time are often too big for harrow control in spring, so that other mechanical control methods have to be used.

In Spain, problems of soil wetness in autumn and in winter are much more seldom, allowing generally weed harrowing at the right moment. In some cases, however, as described by Lacasta *et al.* (1997) wetness occurs and harrowing has to be delayed, so that other techniques as increased row distance allowing hoeing, are more interesting. Otherwise, as found by different authors as Moyano *et al.* (1998), Pardo *et al.* (2001), post-emergence harrowing conducted in autumn or winter can be often an effective weed control method in Spain.

Mechanical control of Papaver rhoeas L.

In the present case, the appearance of herbicide resistance in *P. rhoeas* led to test the harrowing effect on this herbicide resistant weed species. Also the growing social pressure in reducing environmental harmful activities forces to find alternatives to herbicides. An additional reason for thinking on an alternative control method to herbicide use is the need of cost minimisation in cereal production. Especially in years with low weed pressure or in dry years, the chemical control cost might be non-economical.

Previous data on mechanical *P. rhoeas* control by other scientists in different countries including Spain show positive results, encouraging the research. Some of these experiments are quoted in Koch (1964b), Welsh *et al.* (1997) Lacasta *et al.* (1997). Practical experience shows that *P. rhoeas* is a very sensitive species to transplantation, so that the effect caused by harrowing could a priori be high. Additionally, Jones *et al.* (1999) found in laboratory studies that efficacy was superior to 90% when plants with 4 to 6 leaves were pulled out and left on the surface, regardless of the different shading treatments before and after treatment.

Early timing seems to be important for mechanical *P. rhoeas* control in British conditions. Welsh *et al.* (1997) found that tap rooted weeds as *P. rhoeas* were generally better controlled in early development stages in autumn before the plants developed a strong tap root. In Britain, the control of *P. rhoeas* improved when spring harrowing treatments were combined with an autumn harrowing. Additionally, complete burial was found to be important for control, as Jones *et al.* (1995) observed that partial burial gave poor control. These authors found similar efficacy if *P. rhoeas* was pulled out previously to burial with 1 or 2 cm soil than if the weed was only buried. In later works, Jones & Blair (1996) found out that the efficacy was similar for this weed species in wet and in dry soil conditions.

Less detailed information has been found in Spanish experiments regarding *P. rhoeas*. In field experiments conducted in Central Spain on winter cereal, an efficacy of 50-75% *P. rhoeas* control was achieved (Moyano *et al*., 1998). The harrowing treatment consisted in one simple pass conducted in late post-emergence at tillering stage of the crop. Lezaún *et al.* (2001) obtained as well positive results of 66 up to 91% efficacy on *P. rhoeas* in different locations of Navarra (Northern Spain) with single early post-emergence harrowing. Also Zaragoza *et al.* (1999) observed a significant decrease in the overall weed plant number after harrowing in tillering stage of the cereal comparing with the untreated plots as a mean of several field trials conducted all over Spain. However, Lacasta *et al*. (1997) did not find significant differences between the untreated and the harrowed plots on *P. rhoeas* number in a field experiment conducted in Toledo (Central Spain). In this case, the moist soil conditions caused a delay in the harrowing timing reducing the harrowing effect on this weed.

Comparisons between the results of mechanical control field experiments are difficult because many parameters influence the efficacy of these methods. Rasmussen (1990) commented the strong interaction existing between the different implements, driving speed and soil structure, which complicate the interpretation of the results. Other factors affecting the efficacy of these methods are dependent on the weed characteristics as e.g. the initial weed infestations, emergence periods and weed growth stage (Rasmussen, 1996). Kurstjens & Kropff (2001) also point out that environmental influences like wetting and drying of the topsoil and varying timing and amounts of rain will make the impact of harrowing less predictable. Consequently field trial results are less comparable.

Despite all the consulted literature on *P. rhoeas* harrowing, it is thus difficult to define a detailed harrowing strategy for this weed species. Appropriate timing depending on the weed growth stage, the correct intensity, the need of repetition in time and the correct driving speed are some of the topics, which are unclear. Rasmussen (1996) made a detailed description of the weak points of harrowing in general and outlined the need of enriching knowledge of the weed seed bank ecology for improving pre-emergence harrowing and further work on timing and intensity for post-emergence harrowing.

The present study **aims** to be an approach in finding the most indicated harrowing strategy to be conducted in high infestations of herbicide resistant *P. rhoeas* in North-eastern Spain.

Therefor, different harrowing timings in pre-, early and late post-emergence, single and repeated passes, different speed treatments and the use of the roll were combined in different locations. As climatic variability is high between years in the semi-arid conditions, the repetition of similar experiments over several years in the same sites was considered to be very important.

Material and Methods

Description of the field characteristics

A total amount of 11 field trials were conducted during the cropping seasons 1998-99, 1999-00 and 2000-01 on fields with severe herbicide resistant *P. rhoeas* infestations. The crops were winter barley and winter wheat grown in North-eastern Spain (Catalonia) in rainfed conditions. The location characteristics are described in Table 7.1.

All the trials were conducted on commercial fields following the normal farming techniques. Besides Algerri, where the soil had been ploughed prior to sowing, in the other cases the seedbed was prepared using minimum tillage techniques. The average crop density was 450 plants m^{-2} sown in 12 cm row-distances. Sowing date was end of October until beginnings of November and harvest was conducted between end of May (in Torrelameu) until end of June.

Table 7.1.: Description of the location characteristics and of the different treatments of the mechanical weed control trials on *Papaver rhoeas*. Sites with different numbers refer to different fields in the same location. W b: Winter barley, W w: Winter wheat.

Season	Location	Region	Soil type	Plot size (m x m)	Crop	Treatments / Objectives
1998-99	Baldomar 1	Noguera	loamy sand	4.5 x 30	W b	Single timing
	Nalec 1	Anoia	silt loam	4.5 x 10	W w	Single timing, go-and-back
	Torrelameu	Segrià	loam	4.5 x 50	W b	Two timings
1999-00	Baldomar 1	Noguera	loamy sand	4.5 x 30	W b	Single timing
	Algerri	Segrià	silt loam	4.5 x 25	W b	Selectivity (no weeds)
	Nalec 2	Anoia	silt loam	4.5 x 10	W w	Two timings, go-and-back
	Torrelameu	Segrià	loam	4.5 x 25	W b	Several timing, go-and-back
2000-01	Baldomar 1	Noguera	loamy sand	4.5 x 30	W b	Two timings
	Baldomar 2	Noguera	loamy sand	3 x 10	W b	Speed and pre-emergence
	Nalec 2	Anoia	silt loam	3 x 10	W b	Roll, speed, pre-emergence
	Sanaüja	Segarra	silt loam	4.5 x 10	W b	Speed

Description of the treatments

In all the trials a tine harrow trademark Einböck with three independent 1.5 m wide sections was used. The aggressivity of the harrow was adjusted to each soil situation since covering wheel tracks and kept the same in the whole trial.
The field trials were designed in three blocks with randomly distributed treatments. Due to lack of space, the field trials in Algerri 1999-00 and in Torrelameu 1999-00 were designed in two blocks, only.

The main aims of the **first cropping season** were to adjust the harrow aggressivity towards different soil types with and without stones. Also the influence of go-and back passes was studied in order to simulate different intensities based on the results of Böhrnsen (1993) who found that go-and-back passes at the same date increased efficacy. The harrowing was conducted in early post-emergence and in one location also in late post-emergence.

The **second cropping season**, two harrowing timings were studied (early and late post-emergence) also taking into account different intensities by go-and-back passes. Selectivity on the crop was analysed in the experiment realised in Algerri in 1999-00 were no weeds emerged in the field. Post-emergence harrowing was conducted in this field regarding the growth stadium of *P. rhoeas* in neighbour fields.

The **third cropping season**, no go-and-back passes were performed any more but different intensities were simulated with different speeds. The influence of pre-emergence harrowing was tested and the post-emergence was performed at four different speeds of 2, 4, 6 and 8 km h^{-1}. The aim was to find out if there was a relationship between the harrowing speed and the efficacy, as it has been quoted by Böhrnsen (1993) and tested by Rasmussen (1990) in field trials. Rydberg (1994) also tested different speeds in order to achieve different degrees of intensity in weed harrowing, reflecting the generalised opinion on the speed influence.

In one location, the effect of the roll on the harrow efficacy was also tested. Farmers usually roll the fields short time after sowing but sometimes even after crop emergence. In this case, the farmer conducted rolling before crop emergence and pre-emergence harrowing was done afterwards. It was planned to conduct as many harrowing treatments as necessary throughout the cropping season. The very humid winter allowed one late post-emergence spring pass only.

A single post-emergence harrowing treatment was conducted in Baldomar during three cropping seasons. The timing was chosen waiting until most of the *P. rhoeas* plants had emerged and being early enough avoiding that plants were not too big for control. In all three years, the treatment was conducted in late post-emergence. In 1998-99 and 1999-00 the driving speed was around 6 km h^{-1}, while in 2000-01 the treatment was conducted at 8 km h^{-1} as weeds were bigger caused by a delayed timing due to the wet soil conditions.

Table 7.2. summarises the crop, weed and soil stage at the harrowing moment.

Table 7.2.: Crop growth stage, *P. rhoeas* size and soil conditions at the harrowing timings in the different experimental sites. CGS = Crop growth stage.

Cropping season	Location	Treatment	Date	CGS (BBCH)	Weed size (cm)	Soil and weather conditions at harrowing
1998-99	Baldomar 1	Post-emergence	24/03	23-24	3-8	Dry
	Nalec 1	Post-emergence	25/02	13-21	1-3	Very dry
	Torrelameu	Early post-emergence	12/02	21	0.7-2	Dry
	Torrelameu	Late post-emergence	31/03	23-24	3-8	Very dry
1999-00	Baldomar 1	Post-emergence	16/02	21-23	0.7-2	Very dry
	Algerri	Early post-emergence	20/01	13-21	-	Good moisture conditions
	Algerri	Late post-emergence	17/02	21-22	-	Drier, but still good moisture conditions
	Nalec 2	Early post-emergence	29/02	14-22	0.7-3	Quite dry
	Nalec 2	Late post-emergence	07/04	23-24	6-8	Very dry
	Torrelameu	Early post-emergence	13/01	13-14	0.7-1	Good moisture conditions
	Torrelameu	Late post-emergence	17/02	21-22	1-2	Very dry
2000-01	Baldomar 1	Post-emergence	13/02	21-23	0.7-5	The soil had dried out but fog and dew caused moisture again
	Baldomar 2	Pre-emergence	15/11	05-07	01-05	Moist; windy afterwards drying a bit
	Baldomar 2	Post-emergence	13/02	21-22	1.5-3	The soil had dried out but fog and dew caused moisture again
	Nalec 2	Pre-emergence	01/12	07-09	Cotyledons	Almost moist; wind and intermittent sun dried the soil surface out
	Nalec 2	Post-emergence	02/02	23-24	0.7-2	Dry and hard; sunny
	Sanaüja	Post-emergence	13/02	22-23	2-6	Moist; sunny

Assessments

Following Rasmussen (1993), if little intra-specific competition takes place, percent weed control could be calculated both either by density or by biomass decrease. If the intra-specific competition is high, weed control based on density reductions may reflect an unrealistic picture of the weed control if the effect of intra-specific competition is not known. In the present case, weed density was chosen in spite of the high natural *P. rhoeas* mortality, including the plant number evolution in the untreated plots. The main reason of this election was because this non-destructive method allowed to observe plant evolution in time. The measure of the biomass at the end of the season was too much affected by other climatic factors as rainfall, dryness and freezing, so that this final measure was not considered to reflect the harrowing effect properly. It was thus considered that the best measure for efficacy description was plant density taking into account natural weed mortality in the untreated plots.

With the exception of the trials conducted in 1998-99, *P. rhoeas* density was assessed previous to harrowing, In all cases, alive plants were counted after treatment several times. Counts were conducted in 0.1 m^2 frames, 0.33m wide x 0.33m long randomly placed three times per plot each evaluation date. In the trial conducted in Torrelameu in 1999-00, three frames were fixed in each plot in order to increase the assessment precision. In the trials conducted in 2000-01, counts were done in three fixed 1 m x 0.2 m frames per plot. *P. rhoeas* plant number was counted since crop earing. This occurred at beginnings of April approximately, making counts of weeds impossible without damaging the crop afterwards. As climatic conditions promoted crop development in some cases and delayed them in other cases, the last assessment dates differed from field to field and from year to year.

In 1999-00, crop and *P. rhoeas* biomass were sampled at harvest in three 0.25 m^2 frames per plot (0.5 m wide and 0.5 m long) at the end of May in Torrelameu and in Algerri and at the end of June in Nalec. Plants were cut at soil level and taken into separate bags to the laboratory. After air-drying during 3 weeks, whole plants were weighed with a 0.1 g precision balance.

Efficacy calculations

Efficacy was calculated following the Henderson-Tilton formula taking into account the natural mortality in the untreated plots (Ciba-Geigy, 1992). In the first year trials (Nalec 1998-99 and Torrelameu 1998-99) no counts were conducted prior to harrowing. In these cases, efficacy was calculated following Abbott's formula (Ciba-Geigy, 1992). This last formula was also used for efficacy calculations in the pre-emergence harrowing trials Baldomar 2000-01 and Nalec 2000-01 and in the trial conducted in Sanaüja in 2000-01.

[$\%\text{efficacy} = (1- Ta/Ca \times Cb/Tb)*100$] [$\%\ \text{efficacy} = (1-Ta / Ca) \times 100$]

Henderson-Tilton Abbott

Where:
Tb is the infestation in the treated plot before treatment
Ta is the infestation in the treated plot after treatment
Cb is the infestation in the control plot before treatment and
Ca is the infestation in the control plot after treatment.

Statistical analyses were performed on the plant number evolution in time with the SAS system using the ANOVA test and the Duncan means separation in case of significant differences (SAS, 1991).

Climatic data

The general climatic characteristics of the three cropping seasons were lack of rain in autumn but some rain in winter in 1998-99; some rain in autumn but long drought during the whole winter in 1999-00; very moist autumn and winter in 2000-01 (Figures 7.1.-7.5.). The Figures 7.6.-7.10. show the accumulated precipitation in the different seasons visualising the commented observations.

The drought of the first two years delayed and reduced *P. rhoeas* emergence. More aggressive harrow adjustments had to be done in order to scratch the dry hard soil surface, but there were no other difficulties in harrowing when weed plants were still small. *P. rhoeas* emergence in 2000-01 was much earlier and also higher. Soil moisture made harrowing in early post-emergence impossible and weed plants were therefore bigger than desired in the later post-emergence harrowing.

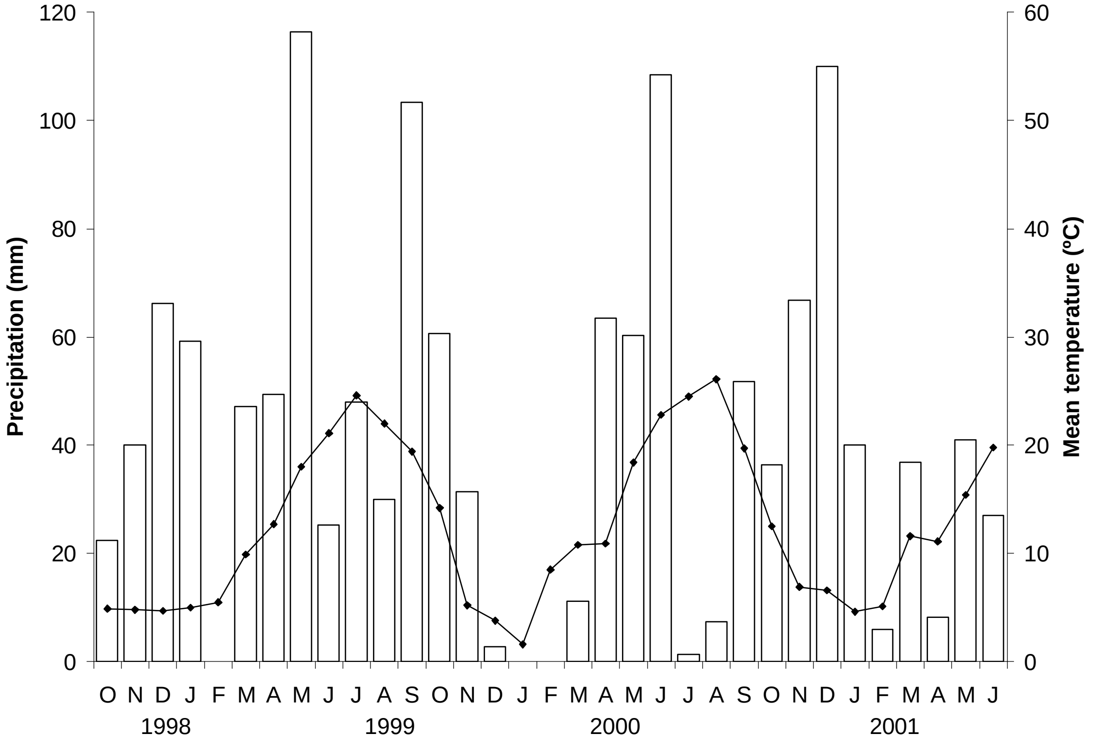


Figure 7.1. Climatic data of Baldomar (La Noguera, Catalonia) during the duration of the experiment. Monthly mean temperature (line) and monthly precipitation (column). Data from the nearby observatory in Vilanova de Meià located at 41.991º latitude, 1.022º longitude and 590 m altitude.

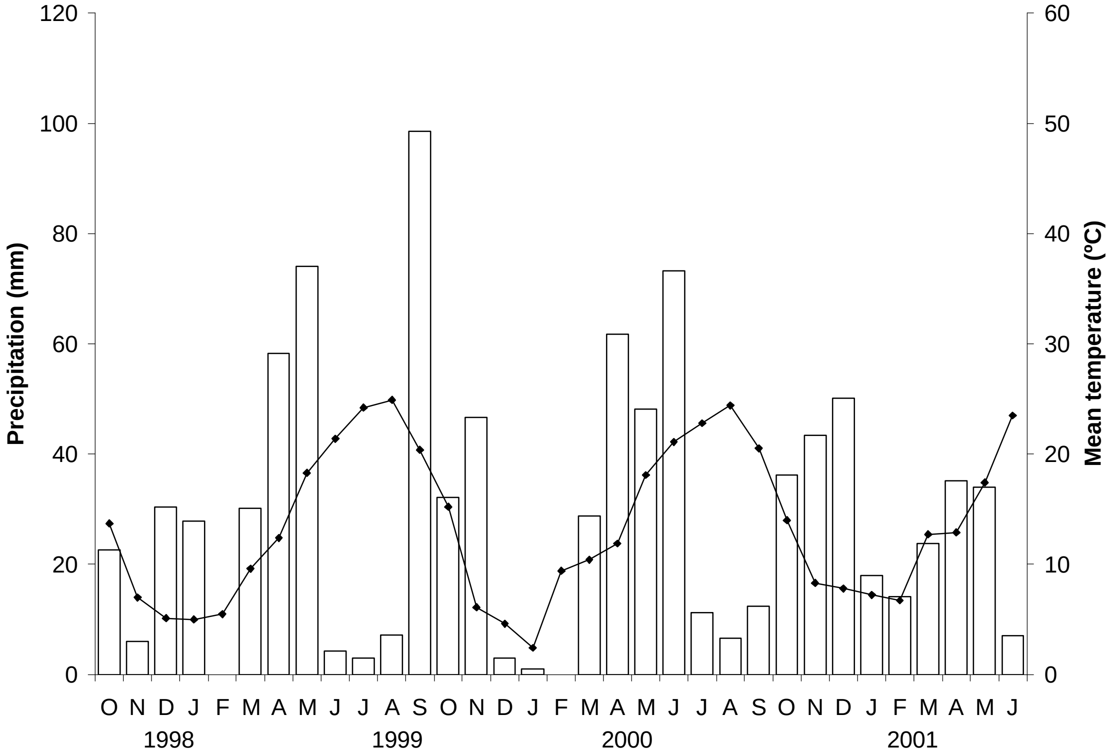


Figure 7.2. Climatic data of Nalec (Urgell, Catalonia) during the duration of the experiment. Monthly mean temperature (line) and monthly precipitation (column). Data from the nearby observatory in Tàrrega located at 41.668º latitude, 1.164º longitude and 420 m altitude.

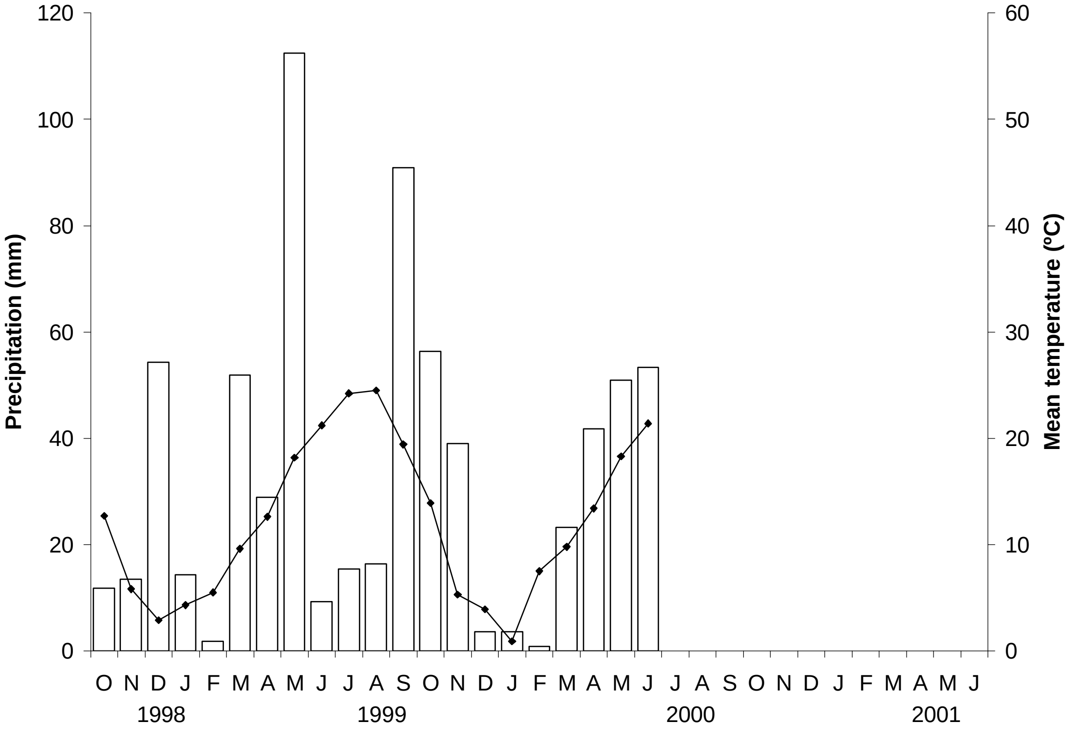


Figure 7.3. Climatic data of Torrelameu (Segrià, Catalonia) during the duration of the experiment. Monthly mean temperature (line) and monthly precipitation (column). Data from the nearby observatory in Vilanova de Segrià located at 41.715º latitude, 0.629º longitude and 218 m altitude.

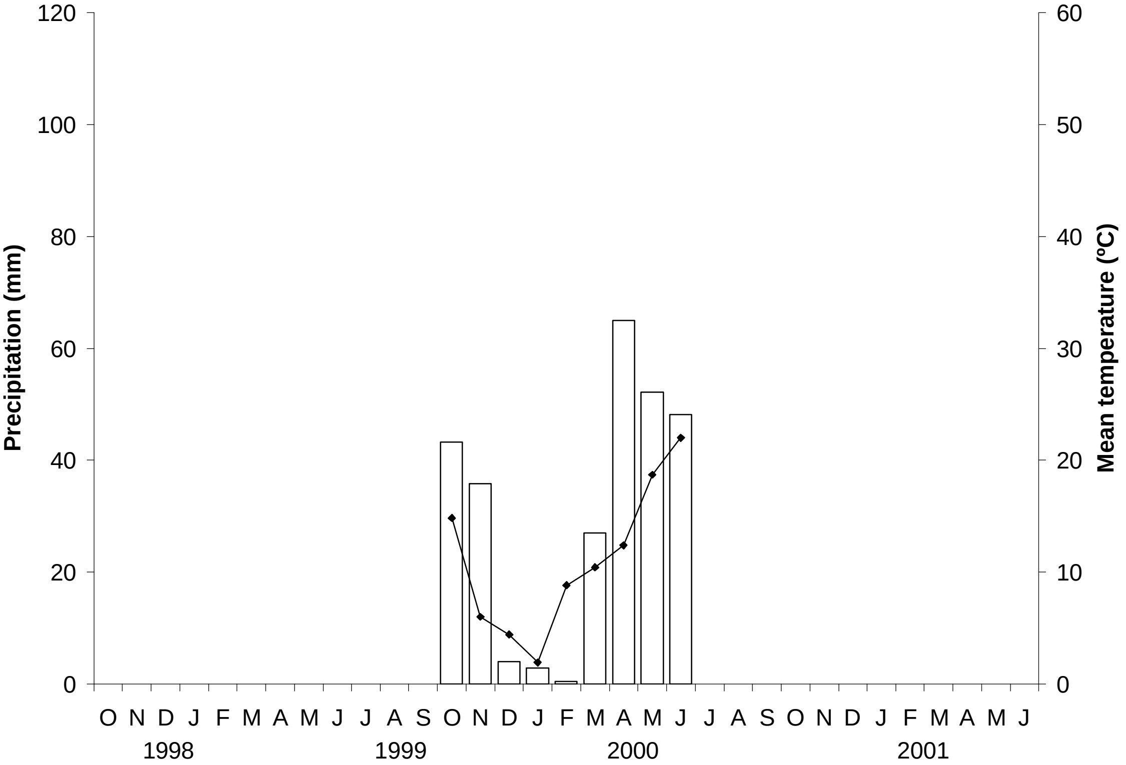


Figure 7.4. Climatic data of Algerri (La Noguera, Catalonia) during the duration of the experiment. Monthly mean temperature (line) and monthly precipitation (column). Data from the nearby observatory in Albesa located at 41.76º latitude, 0.672º longitude and 262 m altitude.

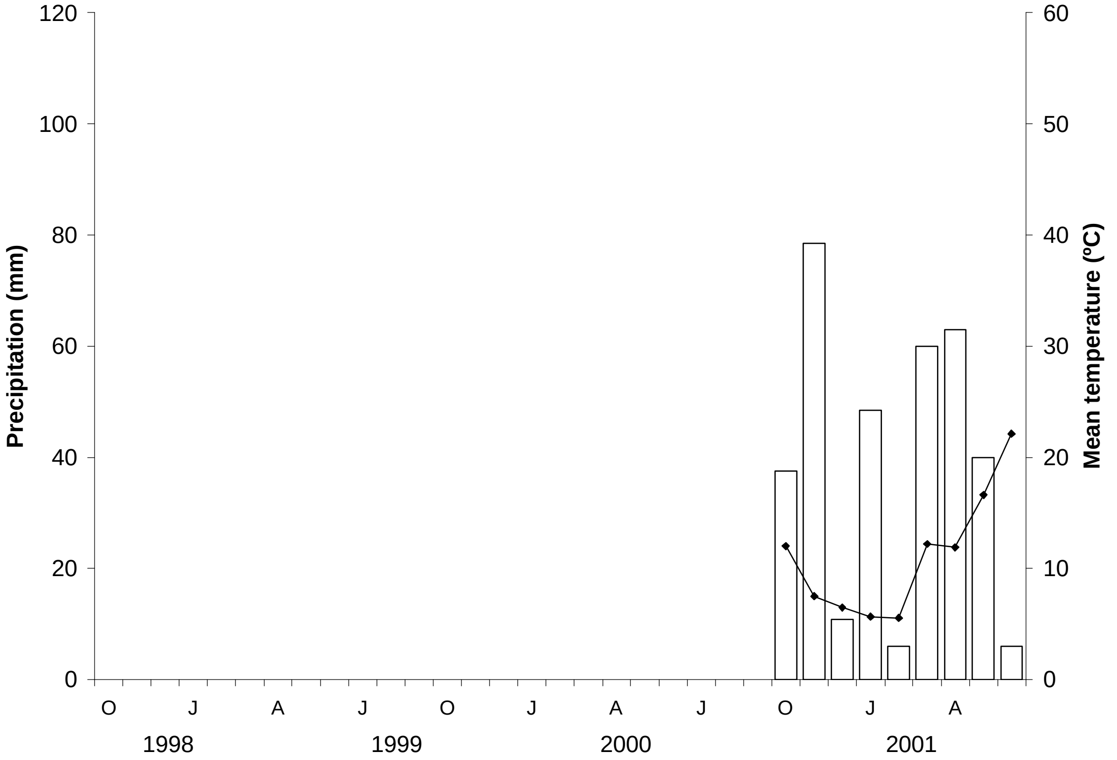
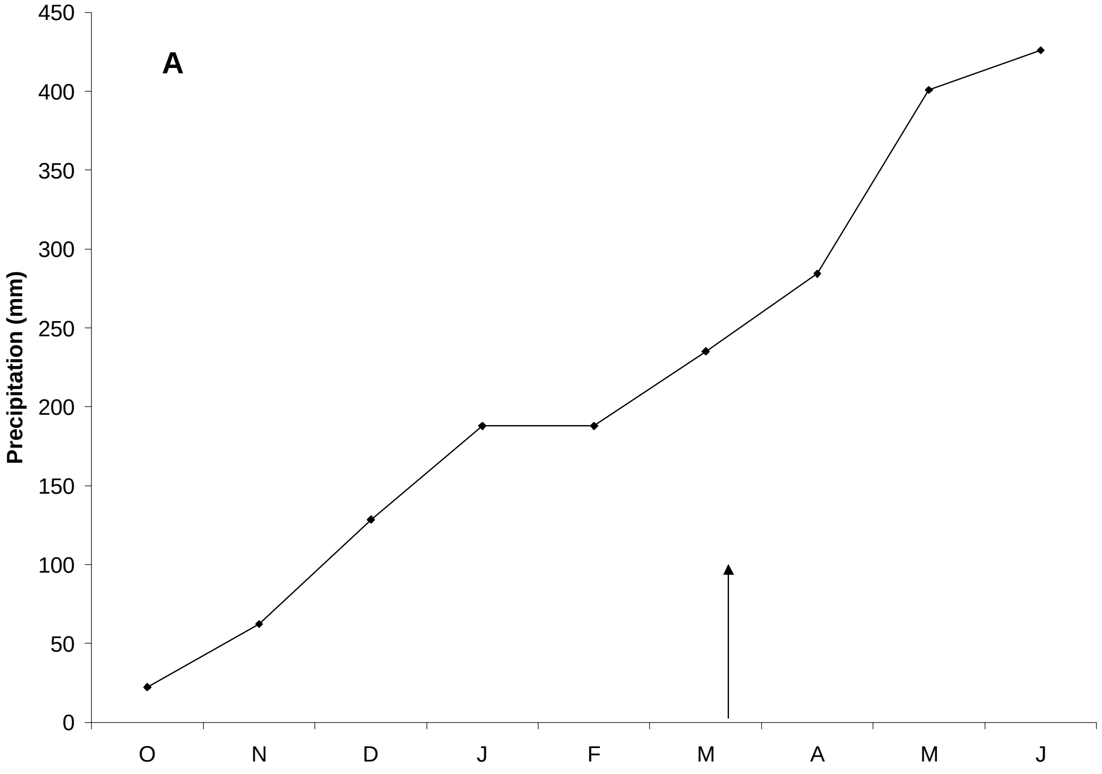


Figure 7.5. Climatic data of Sanaüja (La Segarra, Catalonia) during the duration of the experiment. Monthly mean temperature (line) and monthly precipitation (column). Data from the nearby observatory of Artesa de Segre located at 41.896º latitude, 1.047º longitude and 315 m altitude.

The following Figures 7.6.-7.10. show the accumulated precipitation in the different seasons.



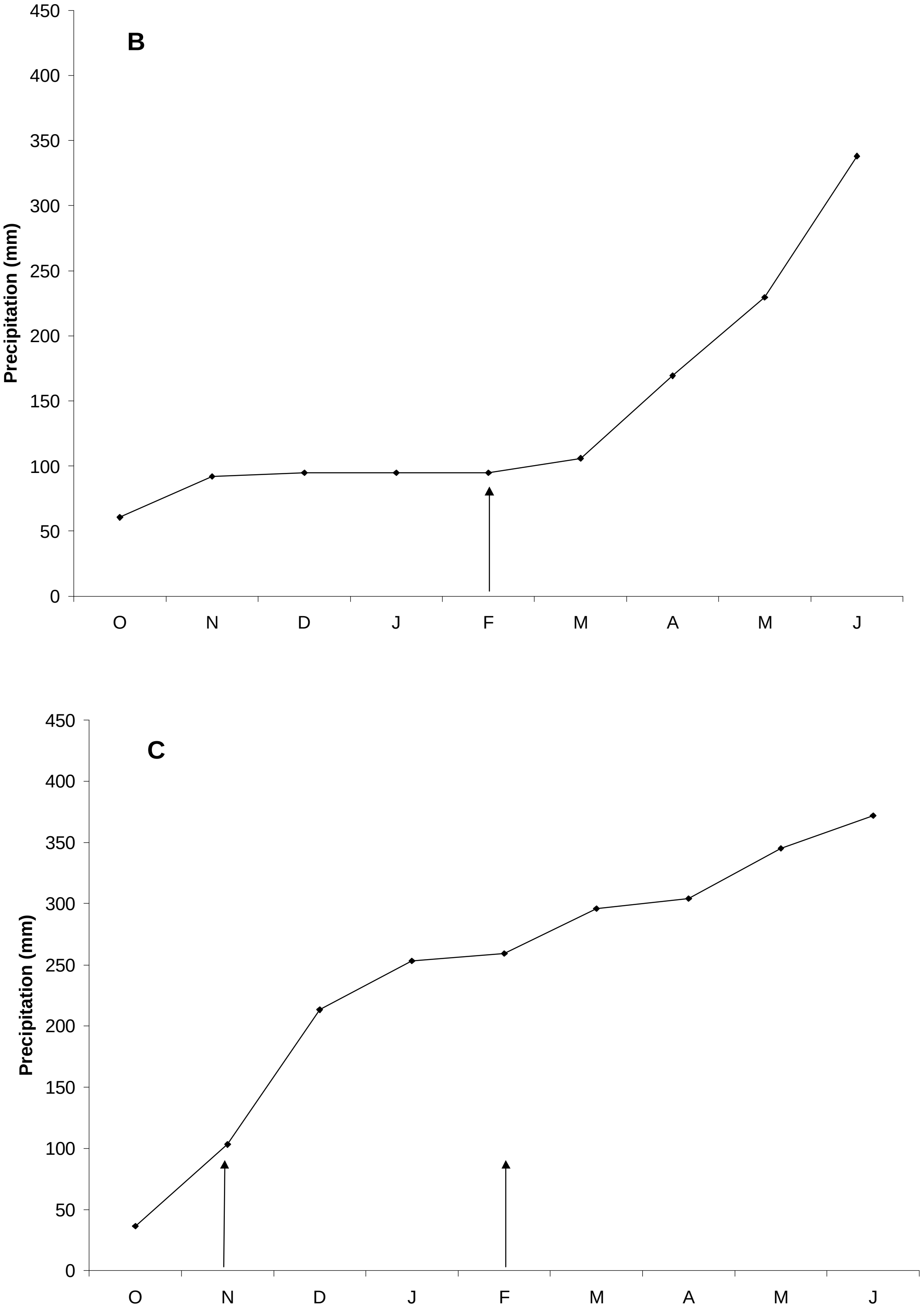
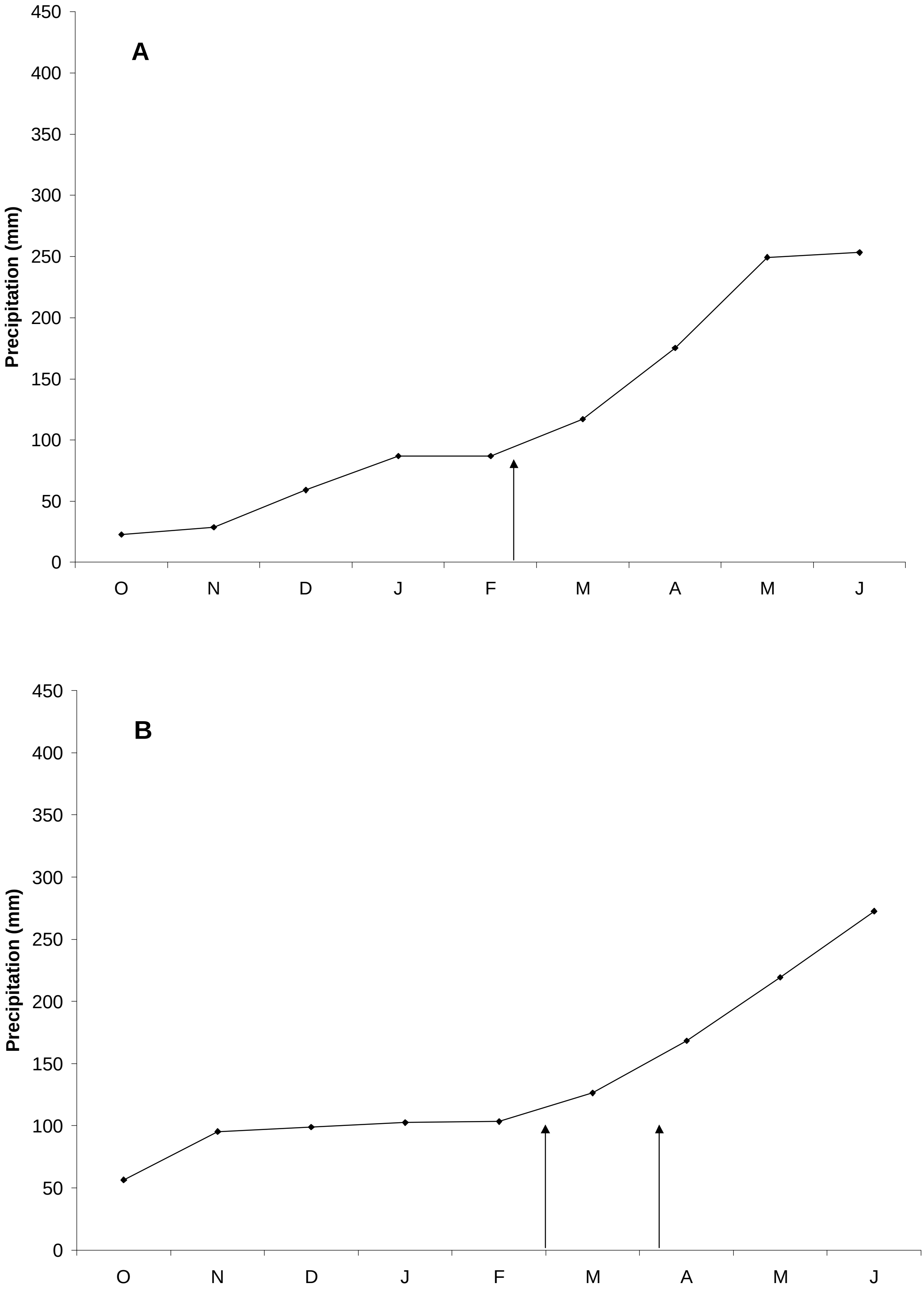


Figure 7.6. Accumulated precipitation in Baldomar (La Noguera, Catalonia) during the cropping season A) 1998-99, B) 1999-00 and C) 2000-01. Data from the nearby observatory in Vilanova de Meià located at 41.991º latitude, 1.022º longitude and 590 m altitude. The arrows indicate the harrowing moment.


A
Precipitation (mm)
450
400
350
300
250
200
150
100
50
0
O
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B
Precipitation (mm)
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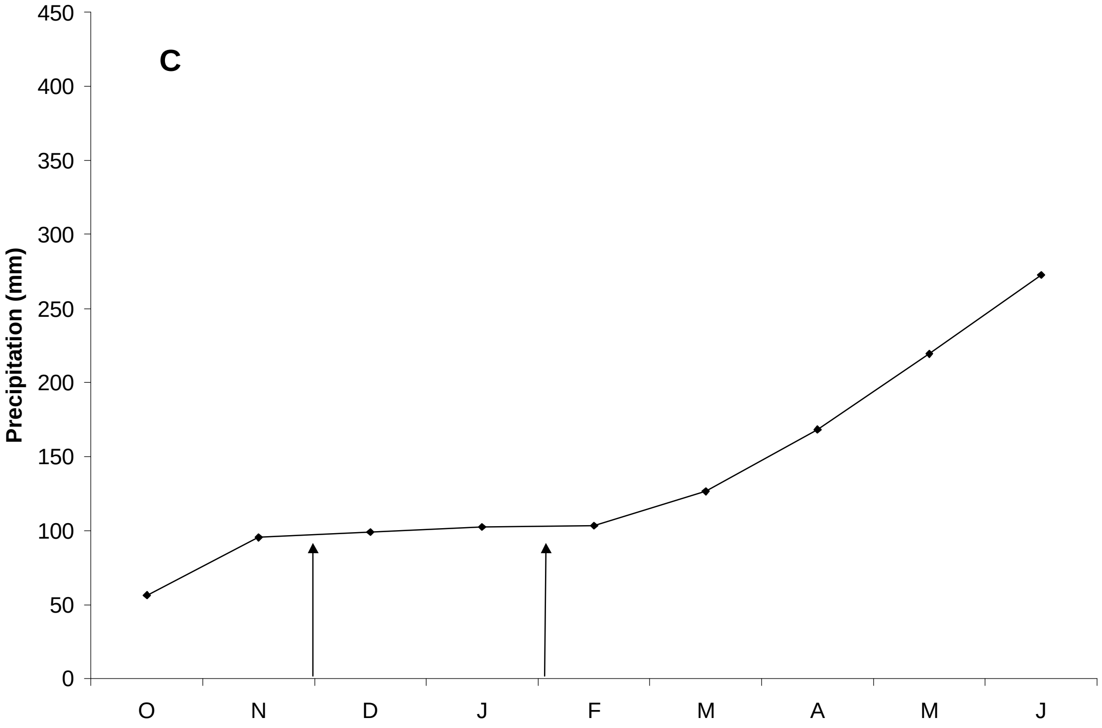

Figure 7.7. Accumulated precipitation in Nalec (Urgell, Catalonia) during the cropping season A) 1998-99, B) 1999-00 and C) 2000-01. Data from the nearby observatory in Tàrrega located at 41.668º latitude, 1.164º longitude and 420 m altitude. The arrows indicate the harrowing moment.

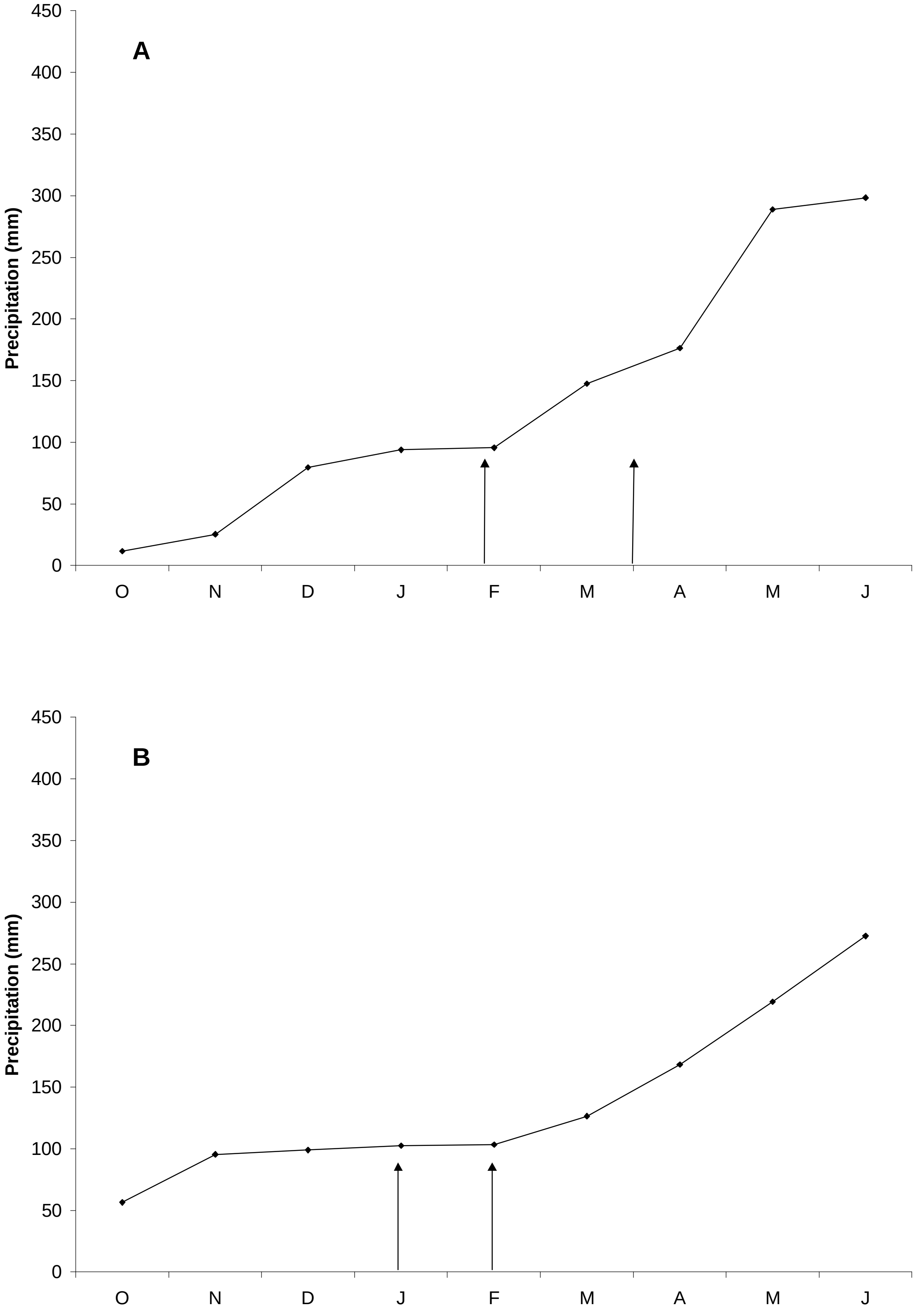

Figure 7.8. Accumulated precipitation in Torrelameu (Segrià, Catalonia) during the cropping season A) 1998-99 and B) 1999-00. Data from the nearby observatory in Vilanova de Segrià located at 41.715º latitude, 0.629º longitude and 218 m altitude. The arrows indicate the harrowing moment.

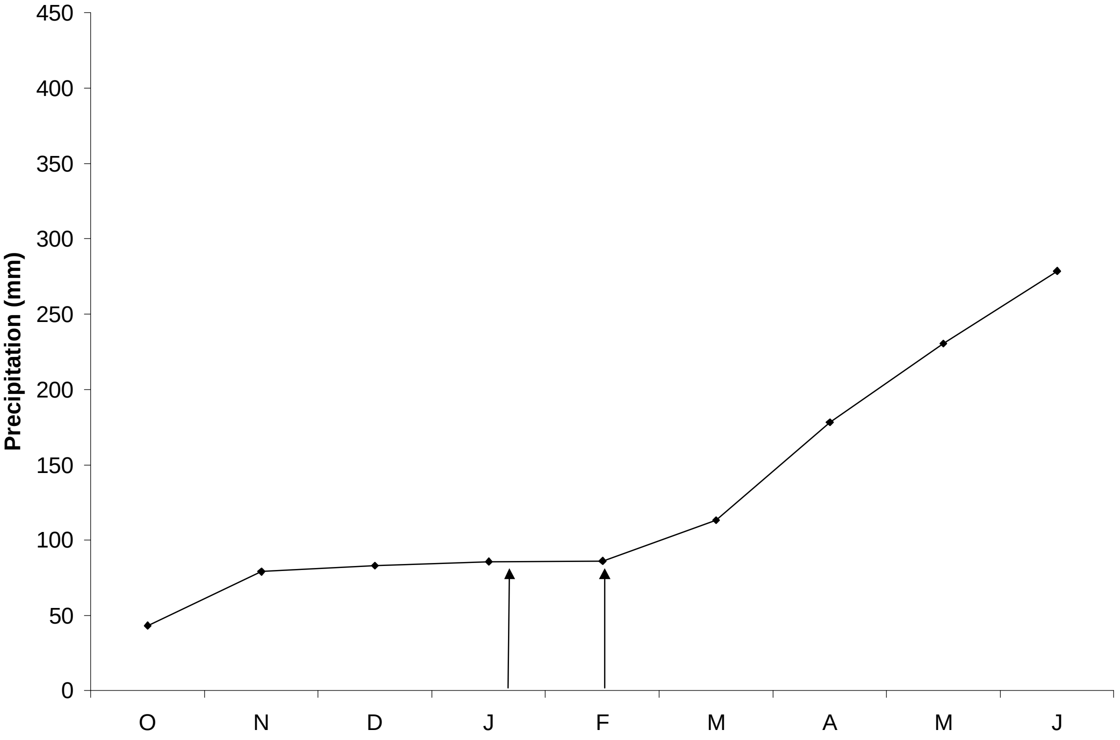

Figure 7.9. Accumulated precipitation in Algerri (La Noguera, Catalonia) during the cropping season 1999-00. Data from the nearby observatory in Albesa located at 41.76º latitude, 0.672º longitude and 262 m altitude. The arrows indicate the harrowing moment.

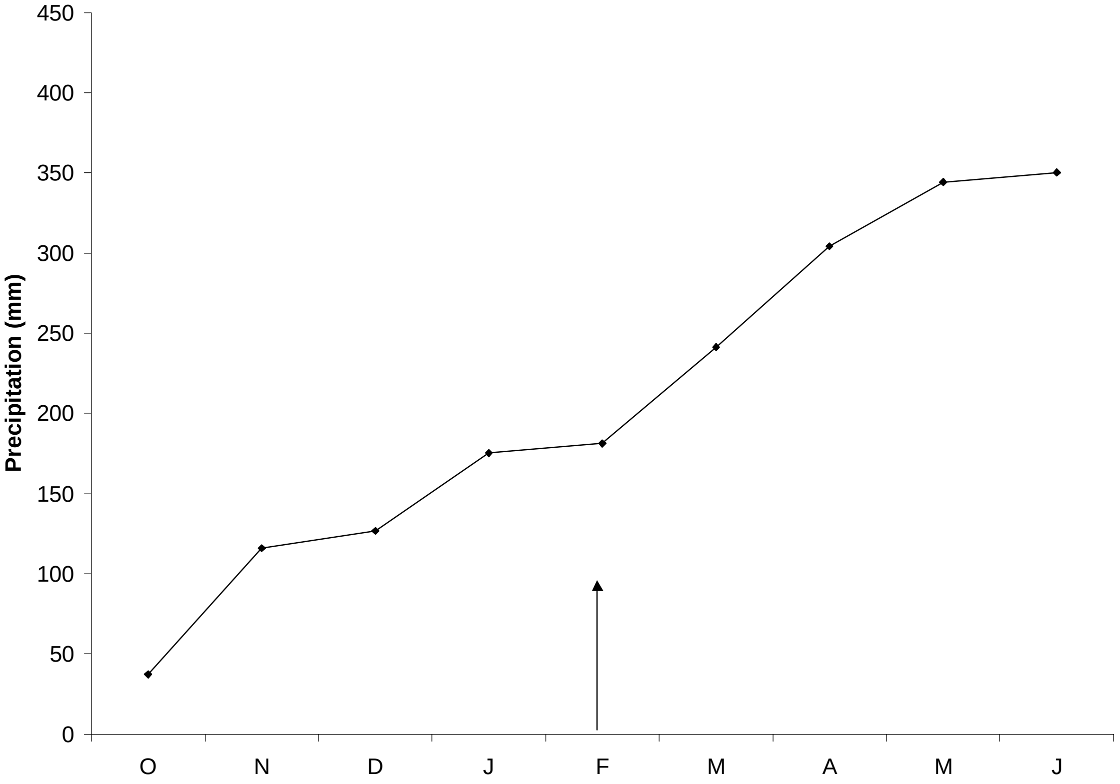

Figure 7.10. Accumulated precipitation in Algerri (La Segarra, Catalonia) during the cropping season 2000-01. Data from the nearby observatory in Artesa de Segre located at 41.896º latitude, 1.047º longitude and 315 m altitude. The arrows indicate the harrowing moment.

Results and Discussion

First year trials

Nalec 1998-99

Data on the first year trial in Nalec are shown in Figure 7.11. Plant density few days after harrowing, corresponding approximately to initial plant number, was around 200 plants m^{-2}. The initial efficacy was around 70% for both treatments 22 days after harrowing, so that in both treatments significantly less *P. rhoeas* plants survived than in the untreated plots ($P<0.01$). Nevertheless, a significant increase in plant number in the single pass treatment after the harrowing could be detected ($P<0.01$). As no clear new germination was observed in these particular plots, this increase was probably due to the recovering of plants which were initially buried by the soil after the harrowing treatment.

The single pass treatment was, thus, not aggressive enough as the final efficacy 41 days after was very low (Figure 7.11.). In both the untreated plots and in the single pass treatment. Plant number decrease since the harrowing but was not statistically significant in the untreated plots nor in the single pass treatment. Only the plant number in the go-and-back pass was still significantly lower than in the untreated plots at the end of the cropping cycle ($P<0.01$) and efficacy reached 75%.

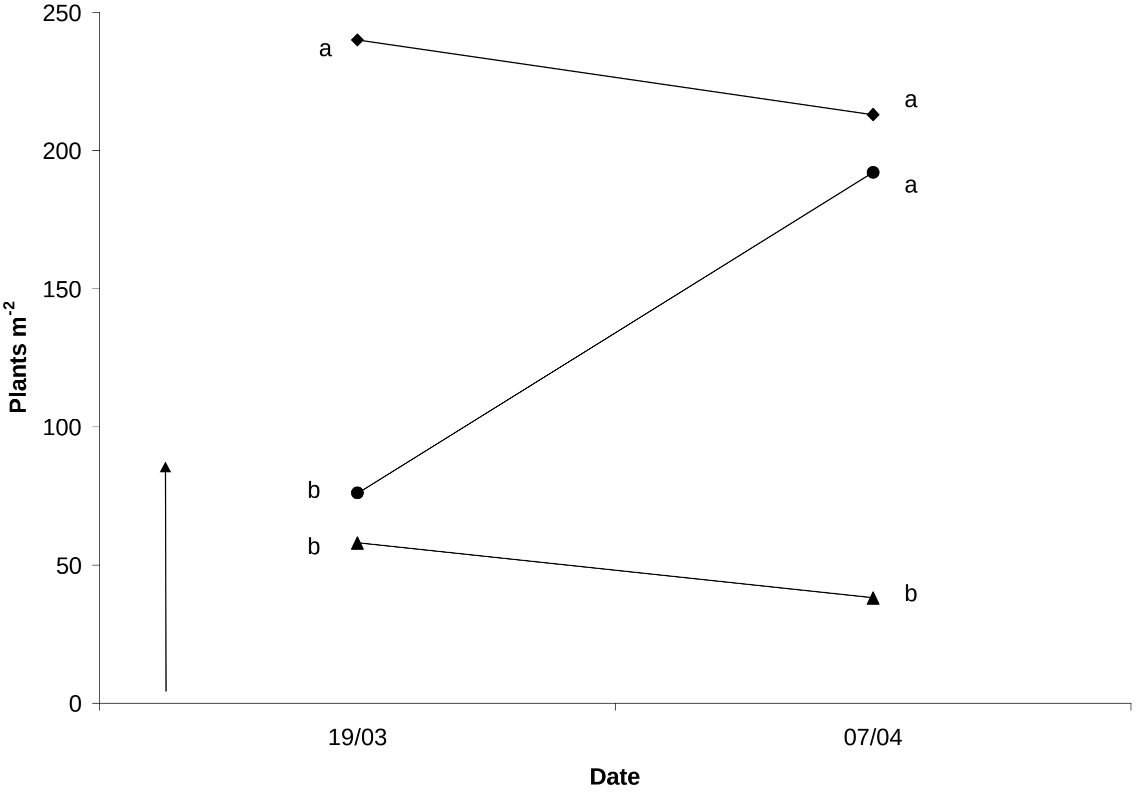

Figure 7.11. *Papaver rhoeas* plant number evolution in time in the field trial conducted in Nalec in 1998-99. The arrow indicates the harrowing moment. ? Untreated, ¦ single pass, ? go-and-back pass. Different letters correspond to statistically significant differences at $P<0.01$.

Torrelameu 1998-99

Also in this trial, no counts prior to early post-emergence harrowing could be recorded. The plant number in the untreated and late post-emergence plots 7 days after early post-emergence harrowing revealed that initial *P. rhoeas* population had been very high reaching around 650 and 1000 plants m^{-2} in the untreated plots (Figure 7.12.). The immediate early post-emergence harrowing effect was a strong reduction of plant number resulting in an efficacy of 60-85%. *P. rhoeas* plant number in the harrowed and untreated plots were statistically different ($P<0.01$). These differences were still significant at beginnings of March ($P<0.05$) but not any more at the end of the cropping cycle. In this trial, promotion of new germination was observed in the plots harrowed in early post-emergence, only. (Table 7.3. and Figure 7.12.).

Table 7.3.: *Papaver rhoeas* density in Torrelameu 1998-99 (plants m^{-2}). Harrowing was conducted in early post-emergence the 12/02/99 and in late post-emergence the 31/03/99. Means of three replicates in the three randomised blocks ± standard deviation.

Assessment date	**19/02/99**	**09/03/99**			**07/04/99**
	Total plant number	Total plant number	Big plants	Small new plants	Total plant number
Untreated	670±260	700±50	700±50	0	331±115
Early post-emergence	97±42	261±221	85±28	176±249	200±78
Early + late post-emergence	259±64	260±115	40±21	220±125	193±101
Late post-emergence	1007±203	621±130	621±130	0	253±85

The new germination resulted in a efficacy reduction, which decreased down to 40% Despite the new germination, no significant differences were detected in the density evolution in time in the untreated, in the early harrowed nor in the early + late harrowed treatments. A high natural mortality was observed in the untreated plots, which did not result in statistically significant differences in time.

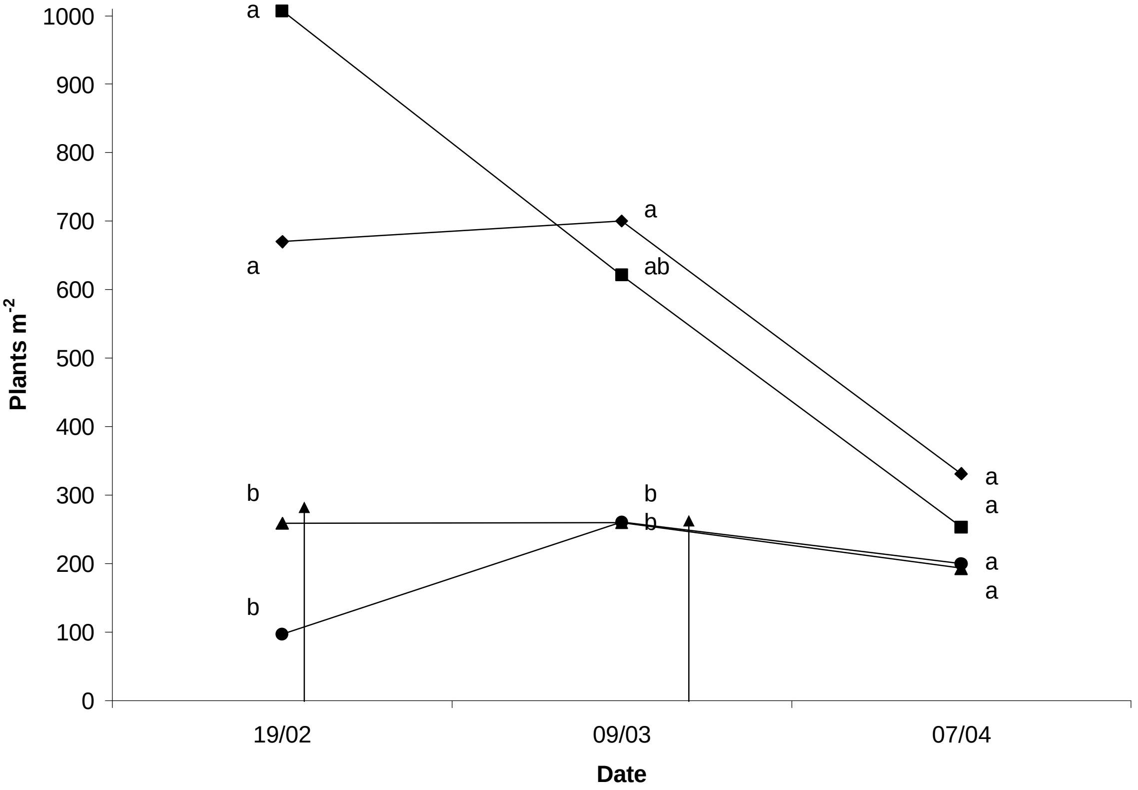

Figure 7.12.. *Papaver rhoeas* plant number evolution in time in the field trial conducted in Torrelameu in 1998-99. The arrows indicate the harrowing moments. ? Untreated, ? early post-emergence, ? early + late post-emergence, ¦ late post-emergence. Different letters correspond to statistically significant differences at P<0.01.

In the late post-emergence harrowed plots, plant number decreased after harrowing in a very similar way compared to the untreated plots. Analysing the plant number evolution in the late post-emergence harrowed plots, significant differences were observed between all three assessment dates (P<0.01). Plant number decrease in the late harrowed plots was probably enhanced by the natural plant mortality.

However, plant number between all treatments was not significantly different at the end of the cropping cycle, so that the harrowing treatments did not cause an important reduction in the final plant density.

Second year trials

Nalec 1999-00

The initial population density was found to be moderate and homogenous throughout the different plots in this trial (Figure 7.13. a) causing no statistically significant differences between treatments. Natural mortality in the untreated plots was not very high compared to other years and locations so that the effect of harrowing alone could be better observed. The early harrowing treatment caused a high initial reduction on the weed population ($P<0.05$) which recovered in the following weeks. In this trial, no new germination was observed for the harrowed plots. Observing plant evolution in time for this treatment, differences were detected between the assessment previous to harrowing compared to the other assessment dates ($P<0.01$).

Differences between treatments were still different at beginnings of April ($P<0.015$) but not any more later on. This was probably due to the combination of plant recovery in the harrowed plots and natural mortality in the untreated plots causing an approach of the densities. The initial high efficacy decreased considerably due to these factors from around 90% down to around 55%. Nevertheless, weed plant number was strongly reduced in the harrowed plots maintaining less competitive levels until the end of the cropping cycle.

The initial population level for the late post-emergence harrowing was similar to the initial densities in early post-emergence. Even if in smaller extent and resulting in statistically non-significant differences compared to the untreated and early post-emergence harrowed plots, the late post-emergence treatment was also very aggressive reducing the *P. rhoeas* population strongly. A surprising increase in plant number was observed after the late post-emergence harrowing in the go-and-back treatment. As *P. rhoeas* does not germinate as late in the present conditions, this effect is probably due to a recover of the buried plants, which were big enough to survive. Nevertheless, this increase was not found to be statistically different to the other treatments neither to its own evolution in time.

Even if final efficacy was very similar for all treatments tested ranging between 50 and 70%, final plant number was considerably but not statistically smaller in the early post-emergence harrowed plots. Probably plants were too big to be well-controlled in the late post-emergence treatment.

Crop dry weight was not statistically different between any treatment (Figure 7.13. b). Crop biomass was quite homogenous both inside treatments and inside the whole field. Some harrowing treatments yielded slightly higher weights, indicating that no important crop damage was recorded as a consequence of harrowing. This field was very stony and harrowing caused stone movement upwards. Despite of this, no problems in crop establishment were observed when harrowed in pre-emergence nor in post-emergence and, as commented previously, no final biomass reduction was found, either.

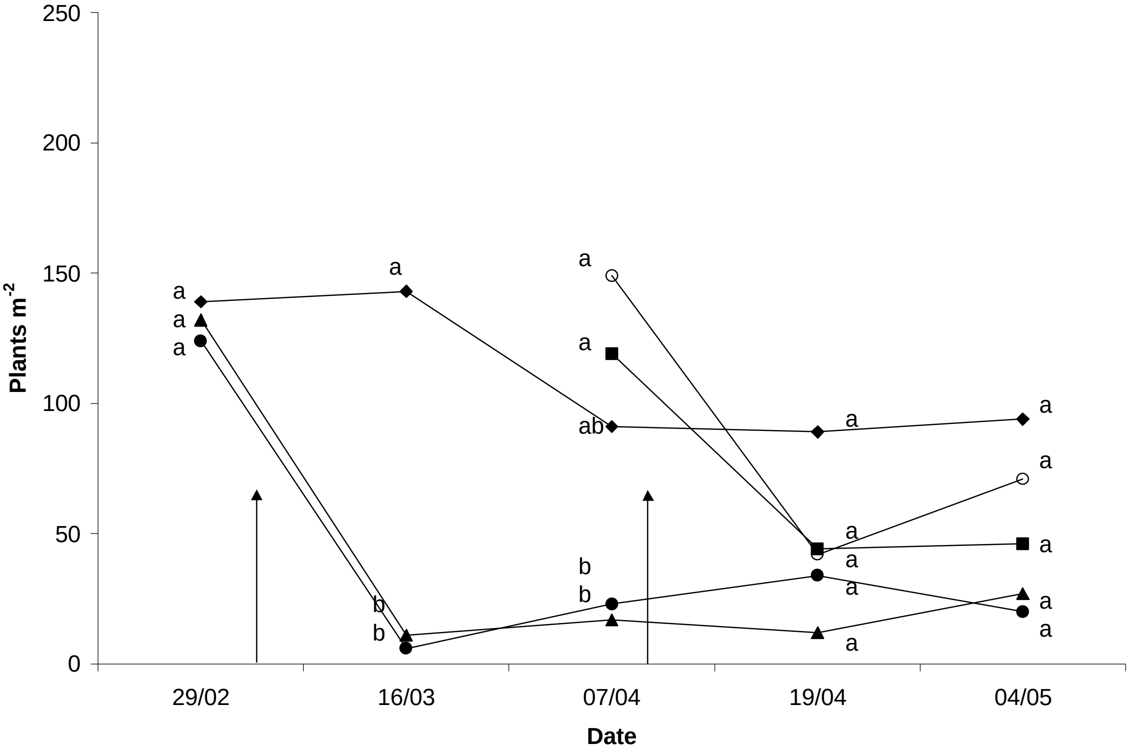

Figure 7.13. a. *Papaver rhoeas* plant number evolution in time in the field trial conducted in Nalec in 1999-00. The arrows indicate the harrowing moments. ? Untreated, ? early post-emergence, ? early + late post-emergence, ¦ late post-emergence, ? late post-emergence go-and-back. Different letters correspond to statistically significant differences at P<0.05.

On the other hand, differences in *P. rhoeas* biomass were found between the untreated plots and the harrowed plots reflecting the harrowing efficacy (Figure 7.13. c). These differences, however, were not statistically significant. Very irregular final plant density and establishment was observed and *P. rhoeas* plants completely disappeared in the early post-emergence harrowing treatments, despite that similar plant number was recorded than in the early + late post-emergence plots some weeks before. This mortality was probably due to other external reasons as drought or competition against the cereal plants.

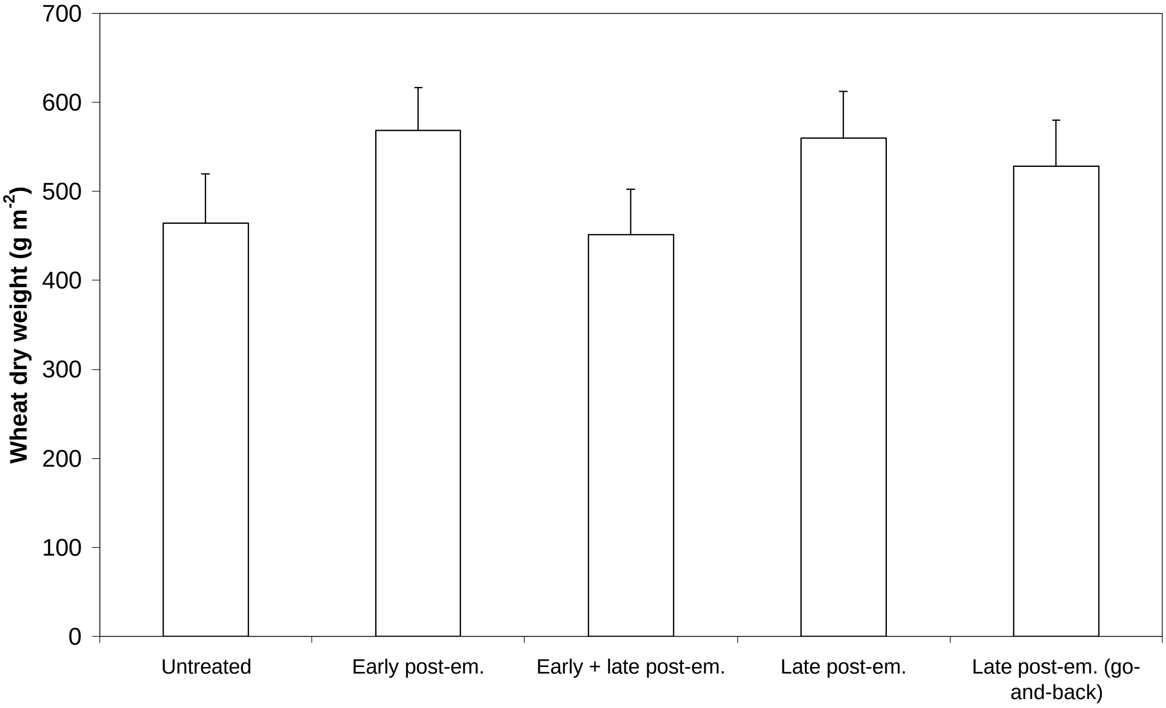

Figure 7.13. b. Wheat dry weight in the trial established in Nalec in 1999-00. Lines indicate standard deviation.

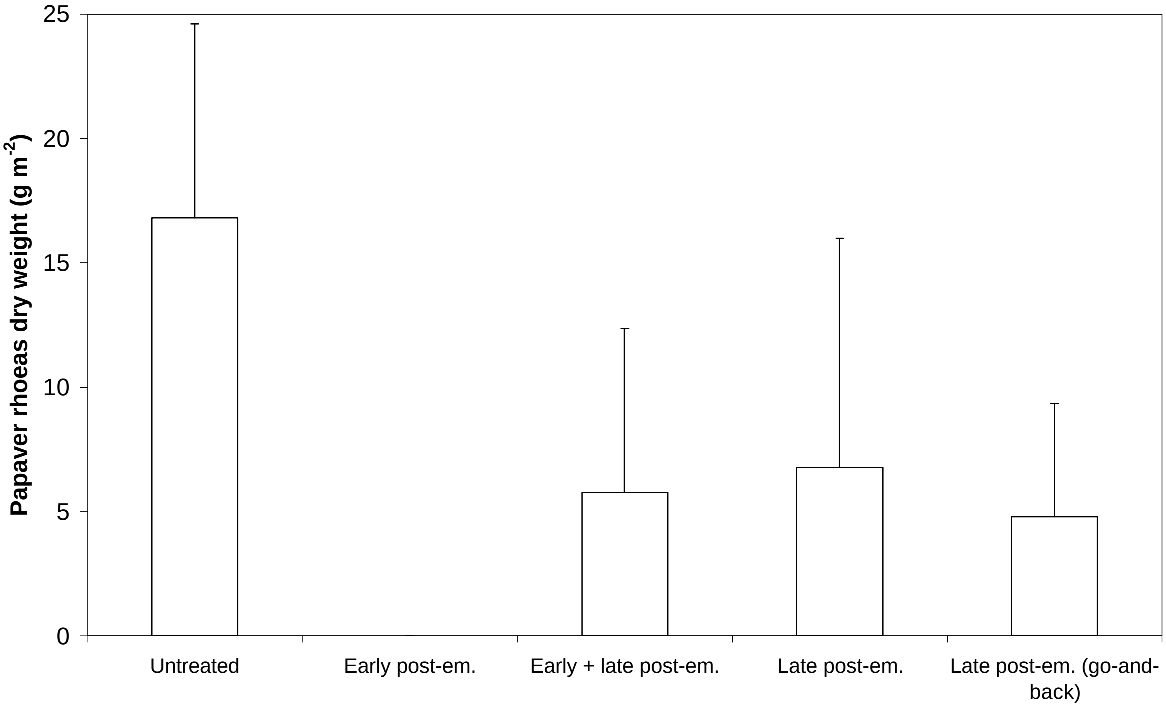

Figure 7.13. c. *Papaver rhoeas* dry weight in the trial established in Nalec in 1999-00. Lines indicate standard deviation.

Torrelameu 1999-00

Initial plant number was regular and homogeneous between the plots, with the exception of the late harrowed plots, in which a higher plant density was recorded, which was not statistically significant (Figure 7.14. a). Population size was big compared to other locations but similar to the same field in the previous cropping season.

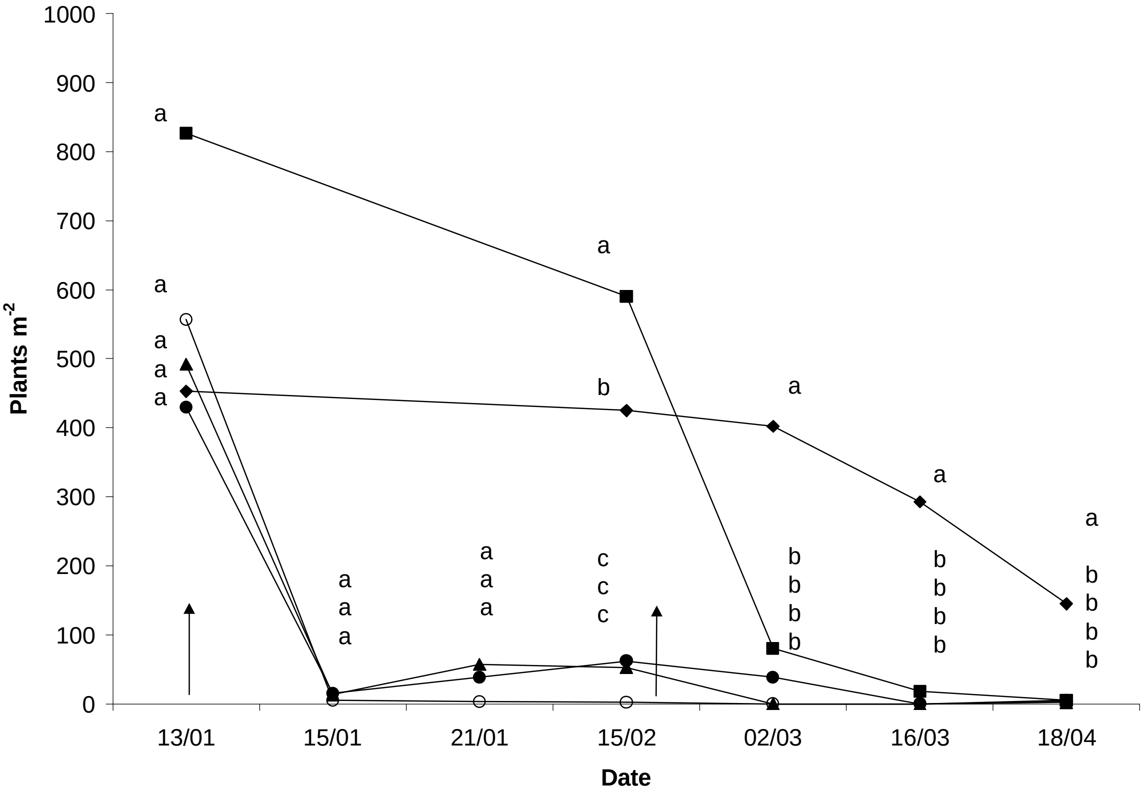

Figure 7.14. a. *Papaver rhoeas* plant number evolution in time in the field trial conducted in Torrelameu in 1999-00. The arrows indicate the harrowing moments. ? Untreated, ? early post-emergence, ? early + late post-emergence, ¦ late post-emergence, ? early post-emergence go-and-back + late post-emergence. Different letters correspond to statistically significant differences at P<0.05.

Both the early and the late post-emergence treatments were very aggressive and reduced the initial high number of plants down to very low plant densities. This process was enhanced by the severe drought, which impeded plants to re-root after being pulled out of the soil or after being buried. Plant population in the untreated plots decreased also due to the drought and to competition but was still closed to 200 plants m^{-2} at the end of the cereal cycle. Plant number evolution in the untreated plots was not statistically significant during this experiment. In the treated plots, evolution of *P. rhoeas* plant density in time showed statistically different values for the counts conducted prior to harrowing compared with the rest (P<0.01). Final efficacy ranged between 95 and 100% for all treatments.

The crop biomass assessments gave very homogenous data, which indicated that no important crop damage was visible at harvest (Figure 7.14. b) and no statistically significant differences were detected. Anyway, the very dry conditions affected the crop so much that possible previous influences were probably hidden by drought. No *P. rhoeas* plant biomass was collected because very few plants survived the treatments.

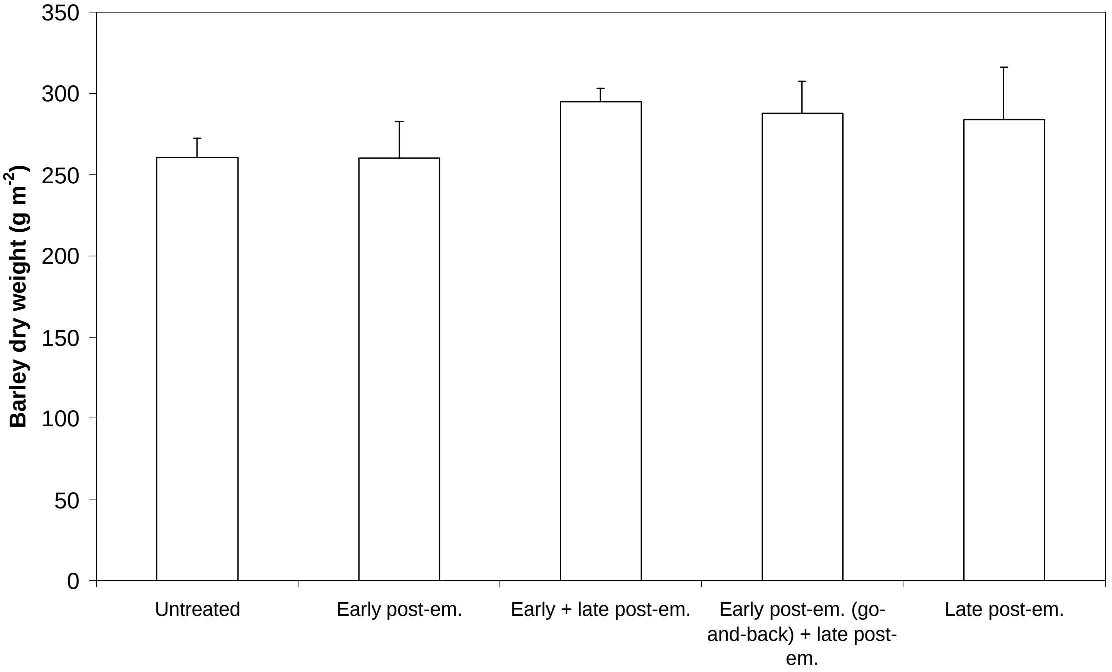

Figure 7.14. b. Barley dry weight in the trial established in Nalec in 1999-00. Lines indicate standard deviation.

Algerri 1999-00

As expected, there was no *P. rhoeas* emergence in this field, but a quite high and homogenous *Avena* sp. infestation was recorded instead. Barley and *Avena* sp. biomass at harvest are shown in (Figures 7.15. a, b). No significant differences in crop biomass were found for any treatment (Figure 7.15. a).

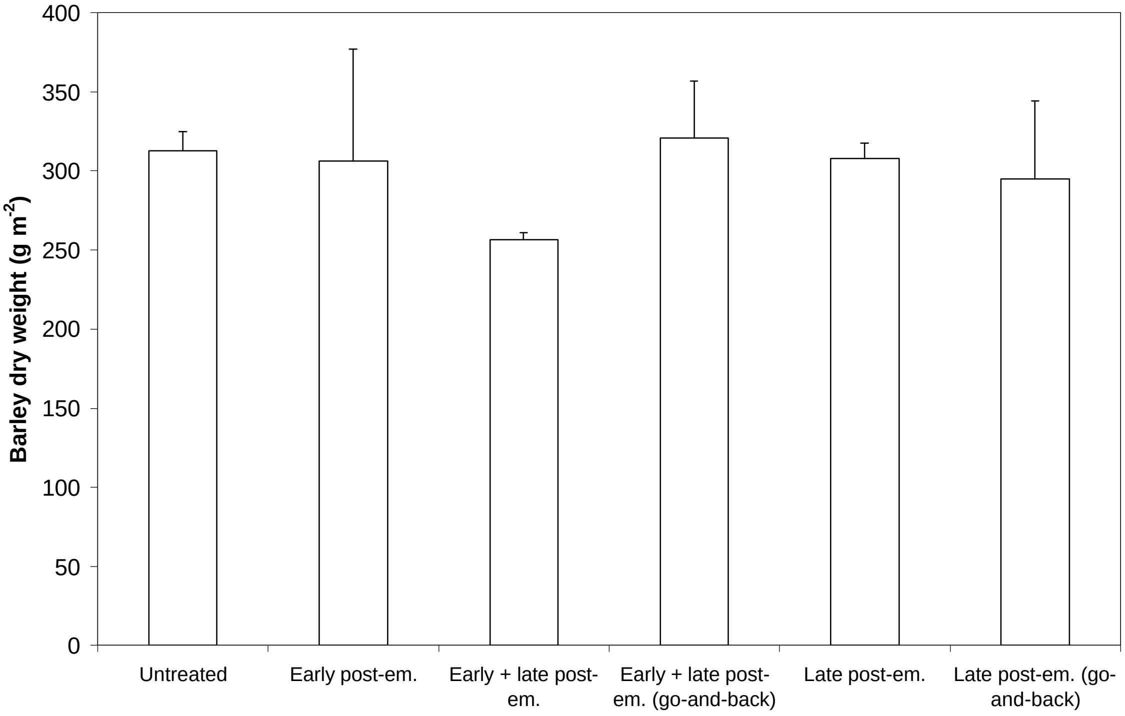

Figure 7.15. a. Barley dry weight in the trial established in Algerri in 1999-00. Lines indicate standard deviation.

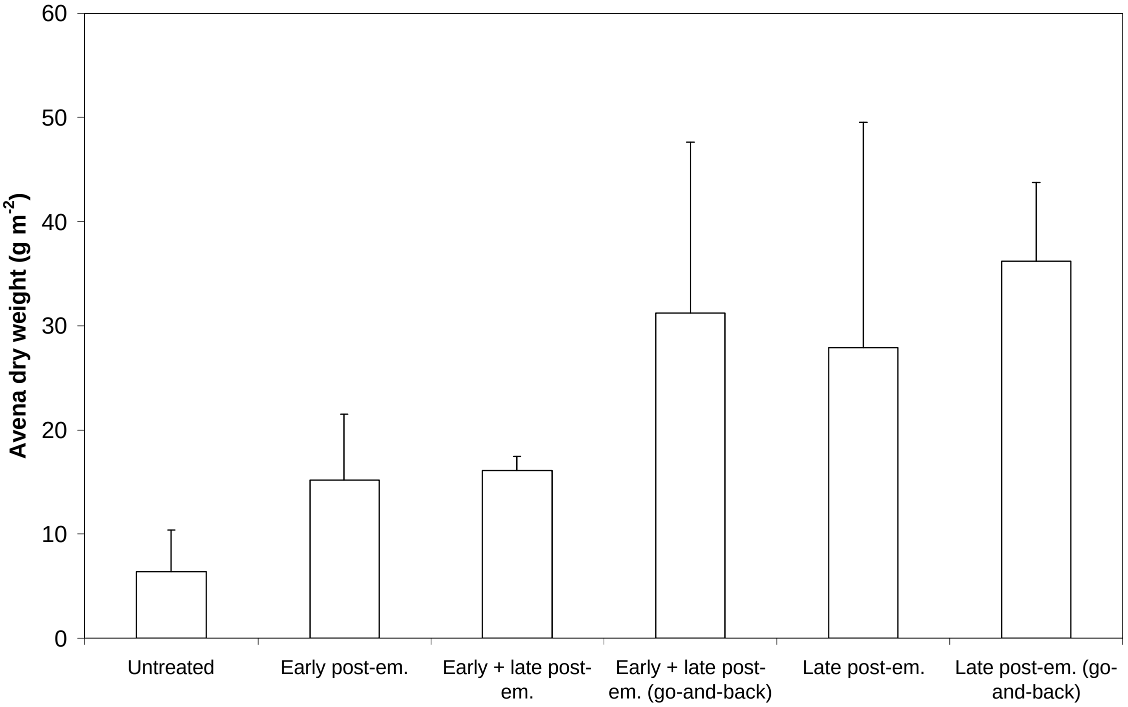

Figure 7.15. b. *Avena* sp. dry weight in the trial established in Algerri in 1999-00. Lines indicate standard deviation.

These results suggest that harrowing, even the go-and-back treatment did not affect crop yield in the tested conditions.

The *Avena* sp. emergence, however, seemed to be related to the late harrowing treatment, which may have stimulated emergence of this weed species even if its irregular appearance between the blocks caused globally non-significant differences (Figure 7.15. b).

Third year trials

Sanaüja 2000-01

Initial plant density ranged between 300 and 450 plants m^{-2} and was statistically not different between treatments. Due to rainfall and to intensive fog, the post-emergence harrowing was delayed in order to conduct the treatment in the proper soil conditions. *P. rhoeas* plants were therefore also bigger than expected at harrowing reducing the weed control capacity of the harrow. Nevertheless, an increased weed control with increasing speed could be observed (Figure 7.16.).

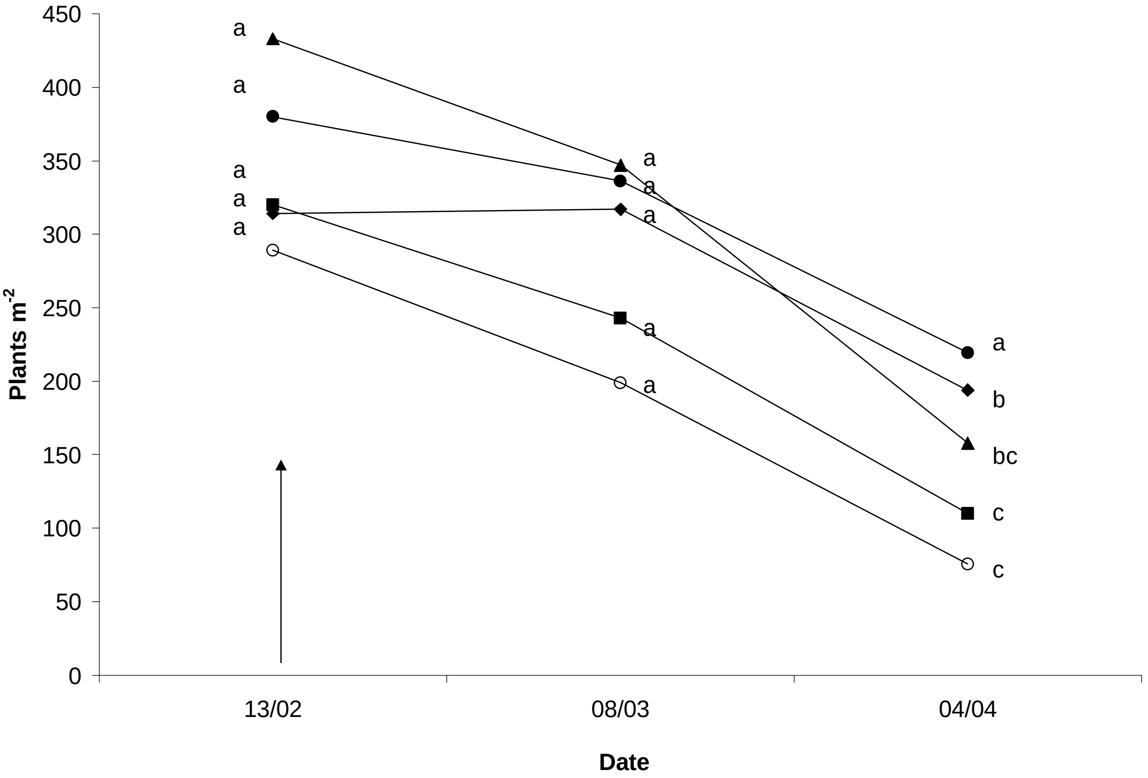

Figure 7.16. *Papaver rhoeas* plant number evolution in time in the field trial conducted in Sanaüja in 2000-01. The arrows indicate the harrowing moments. ? Untreated, ? post-emergence at 2 km h^{-1}, ? post-emergence at 4 km h^{-1}, ¦ post-emergence at 6 km h^{-1}, ? post-emergence at 8 km h^{-1}. Different letters correspond to statistically significant differences at P<0.01.

No late germination was recorded probably due to the good moisture conditions, which facilitated a good cereal development, competing strongly against the weeds making also the recovering of non-killed plants difficult. In contrast to other experiments, in which harrowing efficacy was very high immediately after harrowing, in this case the effect soon after treatment was very low and statistically non-significant (Figure 7.16.).

Opposite to other trials, differences between treatments increased in time finishing with significant differences between plant number at the end of the cycle between the fast harrowed plots at 6 and 8 km h^{-1} and the non-treated plots and plots harrowed at 2 km h^{-1} (Figure 7.16.). The faster harrowing treatments increased efficacy in time, reaching up to 58% in the fastest treatment, while the 2 km h^{-1} treatment maintained an insignificant efficacy level (Figure 7.16., Table 7.4.).

Table 7.4.: Evolution of control efficacy (%) of post-emergence harrowing on *Papaver rhoeas* in the trial conducted in Sanaüja in 2000-01. Efficacy was calculated taking into account the evolution of plant number in the untreated control plots. DAT = days after treatment.

Speed (km h^{-1})	Efficacy 23 DAT	Efficacy 50 DAT
2	12.4	6.7
4	20.6	41.2
6	24.8	44.5
8	31.8	57.8

In all cases, a weed plant number decline mainly due to crop competition was recorded. Probably plants, which survived the fast treatments were more damaged than in the 2 km h^{-1} treatment and could not recover, causing the efficacy increase.

Baldomar 2000-01

In this field trial, **pre-emergence** harrowing was conducted and a pre-emergence herbicide was used 10 days after sowing before crop and weed emergence. The herbicide was very active and *P. rhoeas* plant number was statistically different from the rest of the treatments at almost every assessment date (Figures 7.17. a-d).

P. rhoeas plant density in the plots harrowed in pre-emergence did not differ from the untreated or not yet harrowed plots at any assessment date (Figures 7.17. a-d).

Previous to post-emergence harrowing a great variability was detected in *P. rhoeas* emergence, which even caused statistical significant differences ($P<0.05$) (Figure 7.17. a). This made the pre-emergence harrowing effect even more difficult to be interpreted. Nevertheless, if pre-emergence harrowing had had a clear influence on *P. rhoeas* plant number evolution, this should have been possible to be observed also in this field despite the irregular weed emergence.