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\textbf{ABSTRACT}

A field trial on winter barley, containing a large infestation of a herbicide resistant \textit{Papaver rhoeas} population, was established in North-eastern Spain during the cropping seasons 1998–99, 1999–00 and 2000–01. After decades of minimum tillage, ploughing was conducted in Winter 1998, Winter 2000 or in both 1998 and 2000 in part of the field as a preventive weed control strategy. Plant density assessments and quantification of the seed bank at the end of 3 years were taken. Less \textit{P. rhoeas} emerged in the ploughed plots and the effect was still visible 2 years after ploughing. In the twice ploughed plots, emergence was higher than in the once ploughed plots but lower than in the non-ploughed treatment. Harrowing conducted post-emergence as an annual control method in part of the plots caused a remarkable reduction of the weed population in all three years. The effect caused by the harrowing was more important than the ploughing treatments. However, the combination of single ploughing and harrowing induced the lowest weed plant emergence. The depth distribution of \textit{P. rhoeas} seed was similar for all treatments but there was a higher total seed bank in the twice ploughed plots. Occasional ploughing was found to be an effective method for placing \textit{P. rhoeas} seeds in non-optimal germination situations. When the initial weed seed bank is very high as in this field trial, the reduction achieved by ploughing is not sufficient and an additional weed control method should be conducted.

\textbf{INTRODUCTION}

A rapid increase in herbicide resistance in \textit{Lolium rigidum} Gaud. and in \textit{Papaver rhoeas} L. has been observed in North-eastern Spain in recent years (Taberner et al., 2001). This requires a search for new control strategies. In the case of \textit{P. rhoeas}, herbicide resistant weed populations are often so large, that even

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chemical control with a range of herbicides may not be effective enough. Because of this, it is necessary to integrate different weed control strategies.

Since cereal prices are low and input costs are high, soil seedbed preparation has been replaced by minimum tillage in the study area. In the 1960s it was normal to plough, but cultivation once or twice a year to approximately 10 cm depth is now the most common tillage system. In the experimental field, minimum tillage had been practised for at least the last 20 years, and \textit{P. rhoeas} resistance to 2.4-D and to tribenuron-methyl had led to a very high, almost monospecific and very uniformly infested \textit{P. rhoeas} weed infestation.

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

This burial strategy has been effectively tested in wild oats. After reviewing different tillage experiments, Thill \textit{et al.} (1994) concluded that occasional deep ploughing 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 the surface. Boutsalis & Powles (1998) tested the germination of seeds of \textit{Sisymbrium orientale} populations resistant and susceptible to a sulfonylurea herbicide. A short seed-bank longevity was described for this species, so that in this case periodic seed burial would probably reduce populations if new seed rain was prevented at the same time.

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

To test this strategy with \textit{P. rhoeas} was one of the aims of this study. A similar experimental design was used by McCloskey \textit{et al.} (1991) who, in spite of a very low \textit{P. rhoeas} density, reported that ploughing effectively controlled this weed species.

An additional post-emergence weed control method may need to be combined with the preventive ploughing strategy. In the present study, the effect of ploughing combined with harrowing was tested on a \textit{P. rhoeas} population resistant to tribenuron-methyl and to 2, 4-D. Before the availability 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 to farmers of the study area.

The objectives of this experiment were to study (1) the effect of ploughing on the emergence, depth distribution and survival of \textit{P. rhoeas} and (2) the combined effect of ploughing and harrowing on weed control.
MATERIALS AND METHODS

Field design

The field trial was located on a sandy-loam soil in Baldomar (La Noguera Region, Lleida Province in Catalonia). High and very regular *P. rhoeas* infestations had been observed in this field during the years previous to the experiment and the only tillage conducted in the last years was cultivation. The treatments were ploughing and post-emergence harrowing. The different combinations of ploughing were no ploughing, ploughing in 1998 only, in 2000 only, and in both 1998 and 2000. Ploughing was conducted in strips and the resulting field design was a split-block with three replicates.

Single ploughing in Autumn 1998 or Autumn 2000 allowed the influence of the year of treatment on emergence and distribution of *P. rhoeas* to be tested. Ploughing in both 1998 and 2000 was performed to observe the seed distribution in the soil and the weed emergence with a one-year break in ploughing. The tool used was a two-furrow reversible plough, which turned the soil at approximately 20 cm depth.

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

Ploughing was conducted across the sowing direction whilst harrowing was performed following the sowing lines. Three blocks were established in the sowing direction. The mean of nine observations in each plot was calculated so that 24 values were analysed. Each plot measured 15 x 4 m. Table 1 indicates the dates of each treatment.

Seed emergence and biomass assessment

*P. rhoeas* plants were counted nine times in 0.33 x 0.33 m frames in each 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 1 indicates the dates of each assessment.

In the 1999–2000 cropping season, dry barley shoot biomass was sampled on 25 May 2000, 2 weeks before harvest. One sample of each treatment in each block was taken from 0.5 x 0.5 m frames, dried and weighed. Efficacy was calculated, comparing plant density before and after treatment in the same treated plots.
TABLE 1

Sequence of the different treatments and assessments.

<table>
<thead>
<tr>
<th>Cropping season</th>
<th>Ploughing date</th>
<th>Harrowing date</th>
<th>Seedling emergence assessments</th>
<th>Other assessments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999–2000</td>
<td>–</td>
<td>16/02/00</td>
<td>8/02/00 28/02/00 18/04/00 25/05/00</td>
<td>Crop biomass sampling</td>
</tr>
<tr>
<td>2000–2001</td>
<td>28/09/00</td>
<td>13/02/01</td>
<td>26/10/00 09/01/01 12/02/01 08/03/01 30/05/01</td>
<td>Seed bank soil cores extraction</td>
</tr>
</tbody>
</table>

\[% efficacy = (1-Ta / Tb) \times 100\] where Ta is the weed plant density in the treated plot after treatment and Tb is the infestation in the treated plot before treatment.

Statistical analysis was made using the procedure PROC GLM of SAS (SAS version 8) (SAS, 1991). Standard ANOVA were performed considering a split block design with two treatments with p < 0.05. Previously \( \ln(x) \) transformed data on weed density were subjected to a contrast analysis.

Seed bank characterization

Following Forcella (1992), the ‘glasshouse technique’ was the sampling system chosen for the seed bank characterization. This method consists of keeping the extracted soil samples moist in the greenhouse and recording weed emergence. This technique gives a better correlation with field seedling densities than other methods.

Plastic soil cores of 4.5 cm diameter and 20 cm depth were collected on 26 October 2000 after seedbed preparation corresponding to a sampled soil volume of 318.1 cm\(^3\). The harrowed strips were sampled separately from the untreated strips. Three sub-plots per plot were established and five samples taken in each. After collecting, the cores were emptied in aluminium trays and separated into the upper 10 cm of cultivated soil and the lower 10 cm, which was assumed 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 the soil
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dried. Afterwards, the soil was mixed and rewatered and plants were counted again. A mean value for the three subplots was calculated for each plot. No new emergence was observed after February despite the addition of a gibberellin solution on 6 February 2001 at $0.36 \times 10^{-3}$ g GA$_3$ 1$^{-1}$, a concentration found effective in previous experiments. For statistical analysis a new factor was generated within the experimental plots considering the two depths.

**Climatic data**

The monthly average temperatures and rainfall of Vilanova de Meià, the nearest meteorological station, are shown in Figure 1. During Autumn 1998, enough rainfall was received to allow a moist 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.

The cropping season 1999–00 was characterized by a long drought from December to the end of March. Sowing was conducted in dry conditions in advance of 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 moisture conditions. Autumn and winter rain guaranteed an early and regular crop and weed emergence and establishment. It was difficult to harrow at the beginning of February owing to continuous moisture, which delayed the timing. General data shows that 2000–01 was the cropping season with more rainy days and with the wettest winter. 1998–99 and 1999–00 were both very dry seasons.

**RESULTS**

**Weed emergence**

General *P. rhoeas* density was higher in the cropping seasons 1999–00 and 2000–01 than in 1998–99 regardless of the ploughing and harrowing treatments (Figure 2). In 1998–99, germination started late in February so that emergence was recorded only from March. In 1999–00, as the early winter was very dry, *P. rhoeas* plants started to germinate in February. In 2000–01, autumn and winter were very moist and germination started by late November.

High natural plant mortality was detected in 1999–00 and in 2000–01, especially between February and March. Seedling emergence was recorded from April in the first two cropping seasons and from 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, respectively (Figure 2).

**Ploughing effect**

Ploughing conducted in 1998 reduced weed density (Figure 2). Despite this, at very few assessment times were significant differences found between ploughed and non-ploughed plots, when data was analysed separately for each date (data not shown). The differences were generally greater at the beginning of each cropping season as harrowing was subsequently a more important parameter. However, even if the effect of ploughing in 1998 was difficult to discern at the end of the 1999–2000 cropping season, differences were again greater in winter 2001.

The change in *P. rhoeas* density over the year 2001 under all the ploughing and harrowing treatments is shown in Figure 3. Ploughing in 2000 caused a similar reduction of *P. rhoeas* emergence (Figure 3, Table 2). Plants emerging in the freshly ploughed plots germinated faster than in the other plots (data not shown). This could be an explanation for the initial higher emergence in the plots ploughed in 2000 than in the plots ploughed in 1998 (Figure 3).

Weed density in the plots ploughed in 2000 was the lowest at the end of the
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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 differences compared with the untreated or the twice-ploughed plots were found (Table 2).

Most weed emergence was recorded in the non-ploughed and the twice 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, unlike ploughing once only, either in 1998 or in 2000, ploughing twice did not add to a reduction of *P. rhoeas* density (Figure 3). This was also confirmed with the contrast analysis (Table 2), both considering the overall behaviour during the three years and only during the last cropping season.

**Harrowing effect**

Post-emergence harrowing was conducted in quite dry conditions in early Spring 1999 and in Winter 2000. The rainy winter in 2001 delayed the treatment as the soil hardly dried out in weeks. Despite these differences, harrowing was effective in all cases (Table 3). The contrast analysis in Table 2 shows that harrowing
reduced weed density significantly regardless of the year and of the ploughing treatment even if the plots were not ploughed.

The efficacy values were in the range of other experimental results. For the same weed species in a similar climatic area, Lezain 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 2). Thus, harrowing probably killed the late germinating *P. rhoeas* seedlings that started to germinate, and did not favour any new important emergence. This shows that harrowing was probably carried out at the appropriate time. Also in this case, natural weed mortality reduced differences between treatments with time. Despite this, the harrowing effect was still visible from one cropping season to the next, suggesting seed rain reduction.
Contrast analysis for the overall effect of the different ploughing and harrowing treatments of the last counts over the three cropping seasons and for the last two assessments of the cropping season 2000-01. Data on *Papaver rhoeas* density of each year were In (x) transformed for analysis. *: significant differences.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Last assessments of the three cropping seasons</th>
<th>Last two assessments of the cropping season 2000-01</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Estimate</td>
<td>Pr &gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>T</td>
</tr>
<tr>
<td>Untreated vs any weed control strategy</td>
<td>-4.18</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Untreated vs ploughing in 1998</td>
<td>-0.99</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Untreated vs ploughing in 2000</td>
<td>-0.35</td>
<td>0.113</td>
</tr>
<tr>
<td>Untreated vs ploughing in 1998 and 2000</td>
<td>-0.12</td>
<td>0.594</td>
</tr>
<tr>
<td>Ploughing in 1998 vs ploughing in 2000</td>
<td>0.64</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Ploughing in 1998 vs ploughing in 1998 and 2000</td>
<td>-0.88</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Ploughing in 2000 vs ploughing in 1998 and 2000</td>
<td>-0.24</td>
<td>0.280</td>
</tr>
<tr>
<td>Harrowing one year only vs. ploughing 2 years</td>
<td>-1.11</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Harrowing vs no harrowing</td>
<td>-3.61</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Harrowing vs no harrowing in non-ploughed plots</td>
<td>-0.68</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Harrowing vs no harrowing in 1998</td>
<td>0.89</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Harrowing vs no harrowing in 2000</td>
<td>0.81</td>
<td>&lt; 0.001*</td>
</tr>
<tr>
<td>Harrowing vs no harrowing in 1998 and 2000</td>
<td>-1.22</td>
<td>&lt; 0.001*</td>
</tr>
</tbody>
</table>

(Figure 2). This was especially so 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 (Figures 2 and 3). In 2001, harrowing had a much more important effect on the final weed plant number than ploughing alone (Figure 3). In 1999 and in 2000, the final *P. rhoeas* plant number after either ploughing or harrowing was the same. In fact, following the contrast analysis showed in Table 2, any ploughing and harrowing combination had a significant effect on *P. rhoeas* plant number reduction.

In Figure 4 the mean overall weed density of the three cropping seasons is represented, taking into account either the final assessment of the three cropping seasons or the *P. rhoeas* density of the last cropping season in the last two assessments. The Student-Newman-Keuls test clearly shows that harrowing was
TABLE 3

Percentage efficacy of the post-emergence harrowing treatment on *Papaver rhoeas* in each ploughing treatment and percentage of mortality in the untreated plots. DAT = days after treatment. Mean ± SE.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>March 1999</td>
<td>36</td>
<td>44.6 ± 13.52</td>
<td>25.7 ± 18.65</td>
<td>-</td>
<td>-</td>
<td>6.8 ± 14.21</td>
</tr>
<tr>
<td>February 2000</td>
<td>12</td>
<td>72.3 ± 18.94</td>
<td>67.7 ± 24.30</td>
<td>-</td>
<td>-</td>
<td>8.7 ± 42.95</td>
</tr>
<tr>
<td></td>
<td>51</td>
<td>81.4 ± 3.60</td>
<td>89.7 ± 4.50</td>
<td>-</td>
<td>-</td>
<td>66.4 ± 5.99</td>
</tr>
<tr>
<td>February 2001</td>
<td>23</td>
<td>60.6 ± 3.33</td>
<td>44.2 ± 17.80</td>
<td>49.3 ± 7.93</td>
<td>65.2 ± 8.01</td>
<td>-14.3 ± 7.96</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>63.9 ± 3.14</td>
<td>60.8 ± 21.84</td>
<td>50.2 ± 1.22</td>
<td>57.4 ± 12.10</td>
<td>33.5 ± 1.65</td>
</tr>
</tbody>
</table>
the most effective control method regardless of the ploughing treatment. Ploughing also reduced weed density but in a less regular way (Figure 4).

**Seed bank characterization**

Compared with other studies in winter cereal, a very high seed bank was found, reaching 18000 seeds m\(^{-2}\) from 0 to 20 cm depth in some treatments (Figure 5). As a comparison, 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 22.5 cm depth in winter cereals.

There were no differences in the weed seed content with depth. Despite this, the tendency was to find more weed seeds in the upper layer for the non-ploughed treatment and in the plots ploughed in 1998. A similar amount of seeds was found in the upper and lower layer in the plots ploughed in 2000 and a higher amount of seeds in depth in the twice-ploughed plots (Figure 5).

![FIGURE 4. *Papaver rhoas* plant number change with time under the influence of ploughing and harrowing. Different letters refer to statistically significant differences following the Student-Newman-Keuls test at $p < 0.05$. 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). P 98: ploughed in 1998; P00: ploughed in 2000; P 98+00: ploughed in 1998 and 2000; NP: no plough; h: harrow.](image-url)
Statistically significantly more seeds (p < 0.01) were found in the lower soil layer of the twice-ploughed plots compared with several other treatments (Figure 5). The weed seed content in the upper soil layer of the plots ploughed in 1998 was also significantly higher than in other treatments. The different ploughing and harrowing treatments had no significant influence on crop dry weight (data not shown).

**DISCUSSION**

As the climatic conditions were more favourable for *P. rhoeas* emergence in 1999–2000 and 2000–01, differences between ploughed and non-ploughed plots were also larger in these cropping seasons than in 1998–99 (Figure 2). *P. rhoeas* seed rain was not prevented from year to year and as both initial and final populations were large, an increase of the soil seed bank occurred. Despite this, the effect of ploughing in 1998 on *P. rhoeas* continued to be visible up to 2 years later. Ploughing had thus probably buried more seeds than were introduced into the upper soil layer during the following two cropping seasons by the seed rain of the surviving *P. rhoeas* plants.
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The ploughing effect on *P. rhoeas* diminished with time in 2001. The reason was probably the high natural weed mortality in all the plots including the untreated ones.

As ploughing was conducted with the same tool in 1998 and in 2000, no difference in the soil mixing or turning was expected. Emergence after ploughing once was indeed very similar regardless of the ploughing year. Slight differences were, however, found in the seed bank suggesting that after ploughing in 1998, the developing plants had the opportunity of germinating and producing seeds so that the accumulation of these new seeds could have caused the amount of seed to increase. Considering that each *P. rhoeas* capsula can contain around 1000 seeds (McNaughton & Harper, 1964) and that each plant can develop around four to ten flowers in the present conditions, the numerical differences are not really so great despite the statistically significant differences. Clements *et al.* (1996) also found a higher overall weed seed bank in plots ploughed during eight subsequent years compared with minimum tillage. These results are apparently not related to the emergence of the weed in the field, where no differences were found between ploughing treatments. Clements *et al.* (1996) also found a lower weed emergence but a higher seed bank afterwards for mouldboard ploughed plots compared with other tillage systems. These results show that there is not always a clear relationship between weed emergence and seed bank.

The behaviour in the twice 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 their secondary dormancy was probably broken. This hypothesis is supported by the observations made by McNaughton & Harper (1964) who reported that dense populations of *P. rhoeas* sometimes appear in the first year after ploughing old grassland; thus, 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 remain viable under buried conditions and that the movement upwards relieves 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 for at least 3 years (un-published data). Thus, as concluded for wild oats by Thill *et al.* (1994), deep ploughing only occasionally would probably be interesting for *P. rhoeas* management.

The presence of *P. rhoeas* seeds at depth in the non-ploughed plots is surprising as only superficial tillage had been conducted in the field during the last decades. Probably the minimum tillage was thus deeper than expected and the coarse soil texture had favoured the accumulation of seeds at depth in the years previous to the experiments. Probably due to the sandy texture of the soil, the plough mixed the soil rather than inverted it. This would explain the lack of differences between the 0–10 cm and the 10–20 cm soil layers. This hypothesis is
supported by the results of Clements et al. (1996) who found the following pattern of weed seed distribution in a field after 8 years of mouldboard ploughing: 37% of the seeds in 0–5 cm depth, 25% of the seeds in 5–10 cm depth and 38% of the seeds in 10–15 cm depth. On the other hand, in a three-year experiment described by Ball (1992), most of the seeds in the mouldboard ploughed plots were found at 10–15 cm depth (53%). But many were still in the upper layers: 27% between 5 and 10 cm depth and 20% between 0 and 10 cm depth.

Concerning the harrowing, the lowest weed control 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 in the first counts of all three years, expressed by the negative efficacy values. This demonstrates 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 3). Despite the efficacy, high *P. rhoeas* densities were found after control due to the huge initial density.

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 reduced the proportion of buried seeds in the 1998 ploughed plots and the effect of ploughing on the seed bank seemed to have disappeared two years after ploughing. Despite this, differences in emergence were visible a few months later. In the 1998 ploughed plots, a quite high germination was also recorded indicating that few seeds had rotted or died in the burial period. This observation is consistent with Barralis et al. (1988), who classified *P. rhoeas* as a weed species with a slow decrease of germination capacity with time. For herbicide resistant *Alopecurus myosuroides*, Moss (1985) concluded that any eradication policy is unlikely to be effective in a cropping system dominated by cereals, owing to the sufficient seed survival of that weed. This is probably also valid for *P. rhoeas*.

Mohler & Galford (1997) observed in their experiments with *Abutilon theophrasti*, *Amaranthus retroflexus* and *Chenopodium album* that soil inversion with a mouldboard plough decreased seed emergence but at the same time increased seed survival of the buried seeds. This could 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 was 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 did not support this suggestion, although it can at least be said that no important reduction of the *P. rhoeas* seed bank up to 20 cm depth was found due to a two-year burial and that seeds were able to germinate after exhumation. This observation is consistent with the results of other authors such as Madsen (1962) and Salzman (1954) who reported the long viability capacity of *P. rhoeas* in buried conditions.
CONTROL OF HERBICIDE RESISTANT POPPY

CONCLUSIONS

Ploughing was considered to be an effective method for placing a proportion of the *P. rhoeas* seeds in non-optimal germination situations but needs to be reinforced by other control methods when weed populations are large. Due to the high survival of seeds of this species in the soil, ploughing should not be repeated within a few years. The results of the seed bank suggest that the soil was mixed and not really turned by ploughing. No clear relationship between emergence and the seed bank was found. Harrowing was a good technique for *P. rhoeas* density reduction in all three years but insufficient due to the high initial weed density. The extreme prolificity and survival capacity of *P. rhoeas* seeds requires the inclusion of as many management strategies as possible for its control.

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References


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