Management of herbicide-resistant Papaver rhoeas in dry land cereal fields

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Management of herbicide-resistant *Papaver rhoeas* in dry land cereal fields

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Abstract *Papaver rhoeas* is the most common dicotyledonous weed in winter cereals in southern Europe. It is an increasing problem due to the appearance of herbicide resistant biotypes to synthetic auxines and/or to sulfonylureas. The development of management strategies that combine both cultural and chemical tactics is required. We evaluated the combination of different strategies for the management of a herbicide resistant *P. rhoeas* population to 2,4-D with high infestation levels during four consecutive seasons, from 2002–2003 to 2005–1006, in a rain-fed winter cereal field in North-Eastern Spain. The experiment included the traditional wheat monocrop and five management systems with different combinations of chemical and physical fallows, delayed seeding with barley, chemical and mechanical control, chisel cultivation and mouldboard ploughing. Weed densities along the season and yield at harvest were measured for each treatment. Our results show that in all systems reductions from 90% to 100% of the weed densities were reached. No yield penalties were detected for the non-chemical systems with harrowing along seasons. Moreover, the last 2005/06 season yields, of 2,183–2,356 kg/ha, were higher than the system with traditional wheat monocrop (1,820 kg/ha). The system with delayed seeding every two seasons had the highest yield, of 4,093 kg/ha, the second season, and no differences with other management systems monitored were found other seasons. Delayed seeding and the different fallows studied showed their effectiveness in reducing weed densities, but always combined with other control methods like chemical control or cultivation. This study shows that effective control of herbicide resistant *P. rhoeas* can be achieved with adequate management programmes that combine two or more different strategies, with less dependence on herbicides. These findings define cultural management strategies to reduce herbicide resistant *P. rhoeas* infestations and to contribute to integrated weed management strategies combining these with other tools.

Keywords Fallow · Delayed seeding · Chemical fallow · Physical fallow · Harrowing · Mouldboard ploughing

1 Introduction

Papaver rhoeas L. is the most important dicot weed in winter cereals in areas of southern Europe that have a Mediterranean climate and is well known for its capacity to reduce cereal yield (Wilson et al. 1995; Holm et al. 1997). The ability of this species to invade, grow, and persist in cereal fields can be attributed to the formation of a persistent seed bank, an extended period of germination, and high seed production (Torra and Recasens 2008).

Herbicide resistant biotypes (to sulfonylureas and synthetic auxines) of *P. rhoeas* are extending across Europe, i.e. Spain (Duran-Prado et al. 2004; Cirujeda et al. 2001), Italy (Scarabel et al. 2004), Greece (Kaloumenos et al. 2009), Denmark and UK (Heap 2009), threatening the profitability of cereal production systems. Moreover, *P. rhoeas* populations resistant to photosystem II inhibiting herbicides have recently been found in Poland (Kucharski and Rola 2007). The appearance of these resistant populations in North-Eastern Spain in winter cereals is related to reduction of cultural methods, a greater herbicide dependence and the implementation of monocrop systems (Taberner et al. 2001).

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Since herbicides alone are often not enough to control this weed, the development of new management tools for herbicide resistant *P. rhoeas* is required (Torra et al. 2008). Some studies have put forward that, in order to develop management strategies for *P. rhoeas*, the combination of two or more control strategies is required (Torra et al. 2008). These tactics and strategies should be specifically designed and tested for each region (Powles and Bowran 2000), especially in Spanish dry land areas where cereal yields are low and alternative crop options to cereals are very limited (Cantero-Martínez et al. 2007).

Various and non-chemical strategies have been proposed to control herbicide resistant *P. rhoeas* populations, i.e. soil ploughing or mechanical control (Cirujeda et al. 2003; Torra et al. 2003). The efficiency of soil ploughing is unequal, as it depends on its repetition during different seasons due to difficulty to obtain a correct soil inversion and the presence of deep *P. rhoeas* seedbank. Mechanical control by harrowing offers a good alternative to herbicides, but its efficiency depends on different factors like the phenological stage of plants, speed of harrowing (Rasmussen 2004), and the timing, weather and soil conditions (Cirujeda and Taberner 2006). The combination of both harrowing and ploughing could not be enough to control *P. rhoeas* at high infestations levels (Cirujeda et al. 2003). Other tactics that have also been proposed for management of herbicide resistant weeds are delayed seeding and the incorporation of a fallow year, chemical or physical (Beckie and Gill 2006). These practices can promote a depletion of seed bank and better weed control during the next crop season (Gill and Holmes 1997; Daugovish et al. 1999).

The objective of this work was to study the effectiveness of several management systems (chemical and no chemical) to control herbicide resistant *P. rhoeas* populations in winter cereals and provide new data on the effects of individual methods (different fallow types, delayed seeding, harrowing), which should be combined in Integrated Weed Management (IWM) programmes for the control of these populations.

2 Materials and methods

2.1 The experimental site

An experiment was conducted in a commercial winter cereal field with high *P. rhoeas* infestation in Cubells (Lleida) in north-eastern Spain (41º51′N, 0º58′S) at 450 m high. The soil was silty–clay loam (12% sand, 33% clay, and 55% silt), pH was 8.1, and organic matter content was 2.8%. Daily precipitation and temperature were recorded at a meteorological station located 15 km away from the experimental field (coordinates: 41º52′N, 1º10′S). Average meteorological parameters were calculated and used in this study (Fig. 1). In the years preceding the experiment, the field had been under continuous winter cereals and it had been managed with minimum tillage and selective post-emergence herbicides.

2.2 Resistance status of the *P. rhoeas* population

The resistance status of the studied *P. rhoeas* population to tribenuron-methyl and 2,4-dichlorophenoxyacetic acid (2,4-D) was analysed with quick-tests (Cirujeda et al. 2001), greenhouse, and field experiments. It was established that this commercial field contained a *P. rhoeas* population resistant to 2,4-D but sensitive to tribenuron-methyl (Torra et al. 2008).

2.3 Experimental design

The experiment was carried out during four consecutive cropping seasons (2002–2003, 2003–2004, 2004–2005 and 2005–2006) to evaluate the effect of six different weed management systems on 2,4-D resistant *P. rhoeas*. The aim was compare different combinations of cultural practices and chemical and non-chemical weed control methods: crop rotation, chemical and physical fallow years and barley with delayed seeding (3 months), with the traditional cereal monocrop of the study area.

The six management systems compared were: system 1 (W–chemical), wheat monocrop with chemical control; system 2 (WB–chemical), wheat–barley (with delayed seeding in January) with chemical control; system 3 (FWWB–persistent), chemical fallow (persistent herbicide)–wheat–wheat–barley with chemical control; system 4 (FWWB–non-persistent), chemical fallow (non-persistent herbicide)–wheat–wheat–barley with chemical control; system 5 (FWWB–chisel), physical fallow (harrowing and chisel cultivation)–wheat–wheat–barley with harrowing; system 6 (FWWB–mouldboard), physical fallow (mouldboard ploughing)–wheat–wheat–barley with harrowing. All the agronomic details of the six scenarios are specified in Table 1. The chemical systems (1–4) had a rotation of active ingredients for the post-emergence herbicides, following the Herbicide Resistance Action Committee recommendations.

The experimental design was a complete randomised block with three replicates and six plots (8×10 m) per replicate, corresponding to the six management scenarios. A 1 m corridor was left between plots. Cereals (wheat or barley) were sown in November, except in WB–chemical system, where seeding was delayed to the end of January (see Table 1 for details). Wheat cv. ‘Etecho’ was sown at 180 kg ha^{-1} and barley cv. ‘Graphic’ at 200 kg ha^{-1}. All herbicides were applied at commercial doses with a hand-

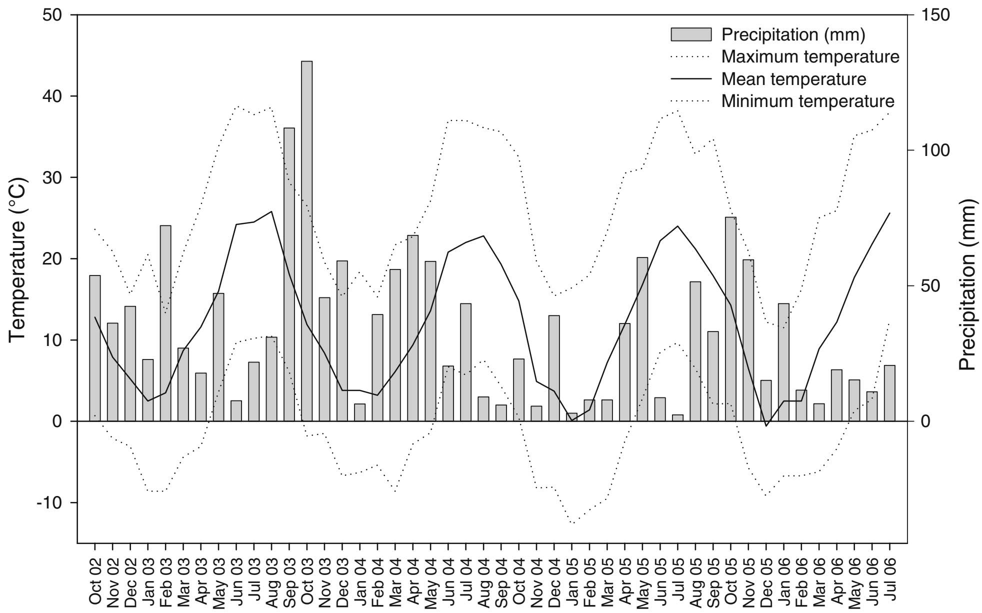

Fig. 1 Average monthly maximum, mean and minimum temperature (°C), and rainfall (mm) over the trial period, from October 2002 to July 2006

field plot sprayer with a 2-m-wide boom with constant pressure at 253 kPa, using a total water volume of 300 L ha^{-1} and flat-fan nozzles. Weed density was estimated periodically in five fixed frames of 0.1 m^2 installed in each plot. Cereal grain yield was measured using a small plot combine harvester 1.5 m wide at the beginning of July. In season 2004–2005, wheat could not be harvested due to a severe drought. The percentage of weed density reduction for each system was calculated dividing the maximum *P. rhoeas* density reached (from the cereal sowing until the control treatment application), and the final density at harvest.

2.4 Statistical analysis

Data were analysed by an analysis of variance (ANOVA) and the means separated using Fisher's protected least square difference at the 0.05 probability level. This was done for each sampling date in the four seasons. Previous to analyses, weed densities and yields were transformed (log $(x+1)$) together with the percentage of density reduction ($\sqrt{(x+0.5)}$) to satisfy the homogeneity of variance assumptions. Back-transformed data will be presented for clarity. The repeated statement option of SAS was used to compare weed densities between sampling dates for each cropping system each season.

3 Results and discussion

3.1 Climatic data

The rainfall for the first season (from October 2002 to July 2003) was 349 mm (with 254 mm over autumn–spring and 94 mm in spring–summer), and in 2003–2004 the overall precipitation was 531 mm (with 283 mm over autumn–spring and 247 mm in spring–summer; data not shown). The rainfall for the third season (2004–2005) was 107 mm, the lowest by far, with 32 mm over autumn–spring and 75 mm in spring–summer. In the last season (2005–2006), the overall precipitation was 277 mm. The total rainfall and its distribution in autumn and winter had a effect on *P. rhoeas* levels each season. Lowest densities were observed the third season, the driest by far. *P. rhoeas* emergence occurs mainly in autumn to winter, and rainfall is one of the main factors that determines its extent and amount (Torra and Recasens 2008). In seasons 2003/04 and 2005/06, rainfalls in October–November were high and frequent, causing the delay in sowing date (16 and 10 days, respectively) in comparison with autumn 2002.

3.2 Weed density

The first season, the highest plant densities (from 1,500 to 2,700 seedlings m^{-2}) were observed in December in all plots just after crop sowing (Fig. 2). During the following weeks, a significant natural mortality was detected (between 21% and 43% of the initial seedling density). In the plots with wheat (W–chemical and WB–chemical systems), *P. rhoeas* densities at treatment time (March 3) ranged between 819 and 908 plants per square meter (pl m^{-2}) and the efficacy of herbicide was higher than 98%. In the rest of the systems, the different control strategies applied on fallow were very effective (higher than 99%), with a nearly absence of plants during the rest of crop season. Only in the FWWB–chisel system (fallow plots with control by harrowing) and FWWB–persistent system (fallow plots with application of a persistence herbicide) a very low density of 2 and 1 pl m^{-2}

Table 1 Cultural practices and weed control methods performed in six management systems for *Papaver rhoeas* in the period 2002–2005 in a commercial cereal field

		Chemical				No chemical	
Season	Date	Wheat monocrop with normal seeding in November W–chemical	Wheat–barley with delayed seeding in January 2nd & 4th year W–chemical	1st year fallow with persistent + selective herbicides FWWB–persistent	Fallow–wheat 1st year fallow with glyphosate + selective herbicides FWWB–no persistent	Wheat–barley 1st year fallow with harrowing and cultivation FWWB–chisel	1st year fallow with ploughing and cultivation FFWB–mouldboard
2002–2003	31 October	Chisel	Chisel	–	–	–	–
	4 November	–	–	–	–	–	Mouldboard
	12 November	Wheat sowing	Wheat sowing	–	–	–	–
	29 January	–	–	–	–	Harrowing	–
	3 March	Iox+bro+mcpp[a]	Iox+bro+mccp[a]	–	Iox+bro+mccp[a]	–	–
	7 March	–	–	Triflur+linur+Iox+ bro+mccp[b]	–		–
	12 March	–	–	–	–	Harrowing	–
	17 April	–	–	–	Glyphosate[c]	–	–
	18 April	–	–	–	–	Cultivation	Cultivation
	14 May	–	–	–	–	–	Mouldboard
2003–2004	27 November	Chisel	–	Chisel	Chisel	Chisel	Chisel
	28 November	Wheat sowing	–	Wheat sowing	Wheat sowing	Wheat sowing	Wheat sowing
	19 January	–	Chisel	–	–	–	–
	21 January	–	Barley sowing	–	–	–	–
	19 February	–	–	–	–	Harrowing	Harrowing
	3 March	Tribenuron[d]	–	Tribenuron[d]	Tribenuron[d]	–	–
	15 April	–	Tribenuron[d]	–	–	–	–
2004–2005	3 November	Chisel	Chisel	Chisel	Chisel	Chisel	Chisel
	15 November	Wheat sowing	Wheat sowing	Wheat sowing	Wheat sowing	Wheat sowing	Wheat sowing
	7 March	–	–	–	–	Harrowing	Harrowing
	15 March	Iox+br+mcpp[a]	Iox+bro+mcpp[a]	Iox+bro+mcpp[a]	Iox+bro+mcpp[a]	–	–
2005–2006	7 November	Chisel		Chisel	Chisel	Chisel	Chisel
	22 November	Wheat sowing		Barley sowing	Barley sowing	Barley sowing	Barley sowing
	20 January		Chisel				
	24 January		Barley sowing				
	21 February					Harrowing	Harrowing
	28 February	Isoprot+diflufen[e]		Isoprot+diflufen[e]	Isoprot+diflufen[e]		
	7 April		Isoprot+diflufen[f]				

Each season fertiliser was applied at 60 UPN in October–November and 70–80 UPN in February

W–chemical wheat monocrop with chemical control, *WB–chemical* wheat–barley with delayed seeding in January with chemical control, *FWWB–persistent* fallow with persistent herbicide–wheat–wheat–barley with chemical control, *FWWB–non-persistent* fallow with non-persistent herbicide–wheat–wheat–barley with chemical control, *FWWB–chisel* fallow with harrowing and cultivation–wheat–wheat–barley with harrowing, *FWWB–mouldboard* fallow with mouldboard ploughing–wheat–wheat–barley with harrowing

[a] Ioxynil+bromoxynil+mecoprop-P [150 g active ingredient (a.i.)ha^{-1} +150 g a.i.ha^{-1} +450 g a.i.ha^{-1}]

[b] Trifluralin+linuron+ioxynil+bromoxynil+mecoprop-P [720 g a.i.ha^{-1} +360 ga.i.ha^{-1} +180 g a.i.ha^{-1} +180 g a.i.ha^{-1} +540 g a.i.ha^{-1}]

[c] Applied at 810 ga.i.ha^{-1}

[d] Tribenuron-methyl [0.015 kg a.i. ha^{-1}]

[e] Isoproturon+diflufenican [135 ga.i.ha^{-1} +126 ga.i.ha^{-1}]

[f] Isoproturon+diflufenican [79 ga.i.ha^{-1} +74 g a.i.ha^{-1}]

was observed, respectively. Apparently, harrowing alone is not a good management tool in a fallow year to eliminate high densities of *P. rhoeas*. In fact, after two harrow passes, too many seedlings were left and finally, a chisel pass was performed (Table 1) to completely eliminate plants and avoid seed production next summer. The ANOVA showed differences between systems for all sampling dates except in the first two (December and November; Fig. 2). Differences were also found between sampling dates for each system (data not shown).

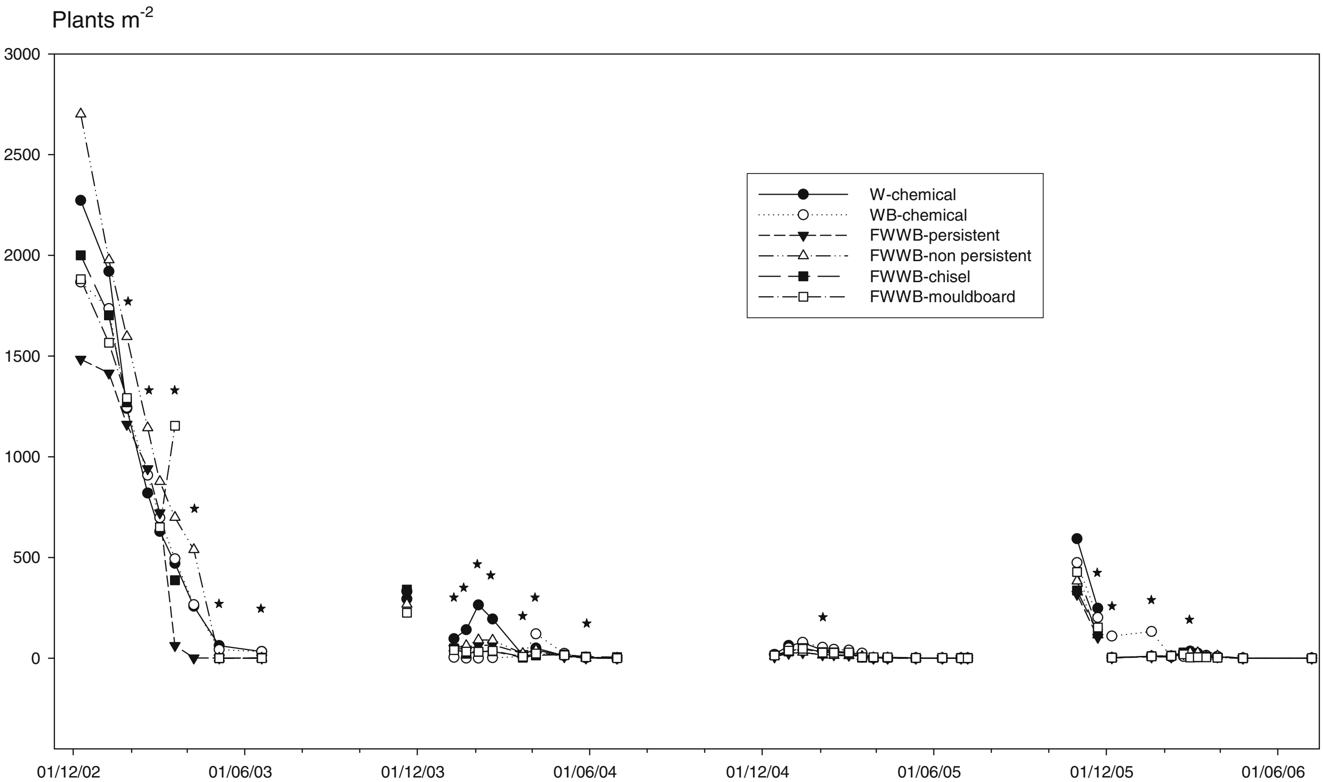

Fig. 2 *Papaver rhoeas* density evolution over time during four seasons (2002–2006) in a winter cereal field. *W–chemical* wheat monocrop with chemical control, *WB–chemical* wheat–barley with delayed seeding in January with chemical control, *FWWB–persistent* fallow with persistent herbicide–wheat–wheat–barley with chemical control, *FWWB–non-persistent* fallow with non-persistent herbicide–wheat–wheat–barley with chemical control, *FWWB–chisel* fallow with harrowing and cultivation–wheat–wheat–barley with harrowing, *FWWB–mouldboard* fallow with mouldboard ploughing–wheat–wheat–barley with harrowing. For more system details, see the section 2. *Stars* significant differences between systems for a specific sampling date

In the second season (2003/04), the initial seedling density in November, before sowing, ranged between 225 and 340 pl m^{-2} (Fig. 2). After sowing, an initial seedling density of 96 seedlings m^{-2} was observed in plots with wheat monocrop (W–chemical), whereas these initial weed densities were lower (approximately of 50 seedlings m^{-2}) in plots with fallow the previous season. During the winter, these densities increased to 264 pl m^{-2} in W–chemical system, whereas in the other IWM systems increases were much lower (Fig. 2). In the plots where barley was sown in January (WB–chemical system), a much lower initial plant density was observed (4 seedlings m^{-2}), and afterwards a significant increase up to 121 pl m^{-2} was detected after sowing. The maximum densities after crop sowing (Table 2) were significantly lower than in the previous season and represented an average reduction of 95% from 1 year to the other. Significant differences in plant densities were found between sampling dates for each system (data not shown).

In the third season (2004–2005), weed densities just after sowing ranged from 6 to 18 pl m^{-2} (Fig. 2). Afterwards, and until control treatments in March, cereal monocrops (systems 1 and 2) showed the highest weed densities (an average of 78 pl m^{-2}), followed by the physical fallows (FWWB–chisel and FWWB–mouldboard systems) with 48 pl m^{-2} and the chemical fallows (FWWB–persistent and FWWB–non-persistent systems) with 28 pl m^{-2}. In spite of these different values, ANOVA only showed statistical differences in one sampling date (beginning of January; Fig. 2). After weed control treatments, *P. rhoeas* densities were very low in all the systems. Significant differences in plant densities were found between sampling dates for each IWM system (data not shown).

In the last season (2005–2006) *P. rhoeas* densities ranged between 317 and 593 pl m^{-2} before sowing at the end of October (Fig. 2). Afterwards, natural seedling mortalities (from 45% to 75%) reduced densities until the end of November to levels ranging from 103 to 247 pl m^{-2}. Cereal monocultures showed significantly higher densities than systems that included a fallow year. During the winter, very low densities (1–3 pl m^{-2}) were found in all systems except in the WB–chemical system, where the crop was not sown until January. Although these plots presented significantly higher weed densities (around 109–132 pl m^{-2}), these populations were much reduced after sowing. In

Table 2 *Papaver rhoeas* densities in six systems monitored during four seasons in a winter cereal field

Management System	02/03			03/04			04/05			05/06		
	Max. initial Density (pl/m^2)	Final Density (pl/m^2)	Reduction of weed density (%)	Max. initial Density (pl/m^2)	Final density (pl/m^2)	Reduction of weed density (%)	Max. initial Density (pl/m^2)	Final density (pl/m^2)	Reduction of weed density (%)	Max. initial Density (pl/m^2)	Final Density (pl/m^2)	Reduction of weed density (%)
W–chemical	2,307±663	33±17	98.7±0.9	268±267	0	100	77±13	0	100	36±10	0	100
WB–chemical	1,867±82	32±19	98.3±1.8	121±46	0	100	78±39	0	100	16±1	0	100
FWWB–persistent	1,518±100	1±1	100±0.1	66±18	0	100	29±13	0	100	25±4	0	100
FWWB–non-persistent	2,701±836	0	100	91±17	0	100	34±9	0	100	30±10	0	100
FWWB–chisel	2,011±377	2±2	99.9±0.2	49±4	5±4	89.7±15	50±19	1±1.2	98.9±2	28±8	0	100
FWWB–mouldboard	1,881±309	0	100	42±7	0	100	49±16	0	100	19±1	0	100

Values are means and S.E

The percentage of reduction of weed density is calculated between the maximum weed density and the final density. No statistical differences were found between management systems each season for the percentage of reduction of weed density. See section 2 for details of each system

Max. initial density maximum weed density reached after the cereal sowing until the control treatment applications, *final density* weed density at harvest, *W–chemical* wheat monocrop with chemical control, *WB–chemical* wheat–barley with delayed seeding in January with chemical control, *FWWB–persistent* fallow with persistent herbicide–wheat–wheat–barley with chemical control, *FWWB–non-persistent* fallow with non-persistent herbicide–wheat–wheat–barley with chemical control, *FWWB–chisel* fallow with harrowing and cultivation–wheat–wheat–barley with harrowing, *FWWB–mouldboard* fallow with mouldboard ploughing–wheat–wheat–barley with harrowing

general, during February and March, densities showed a slight increase, with system 1 showing significantly higher values (34 pl m^{-2}). After the control treatments, all densities were progressively reduced to 0 pl m^{-2} in all systems. Significant differences were found between samplings for each system (data not shown).

The different treatments carried out in the different plots were equally efficient in the reduction of weed density (98–100%) and no statistical differences were found between them (Table 2).

After sowing, *P. rhoeas* densities were much higher the first season compared to the following ones with a general progressive decline from the first to the fourth season. The last season weed emergences before sowing were higher compared to the two preceding, regardless of 100% of density reduction in almost all plots and that no seeds were produced, thus showing the persistence of *P. rhoeas* seedbank (Lutman et al. 2001). This decline was specially marked at the estimations made just after sowing. The lower values of initial seedling density seem to be consequence of the reduction of soil recruitment of seeds, the delay in sowing date in the second and fourth seasons, and the severe drought in the third season. This allowed a great emergence of *P. rhoeas*, 317–593 seedlings m^{-2} in 2003 and 225–341 seedlings m^{-2} in 2004 that, were killed with seedbed preparation and sowing. Thus, during the growing seasons weed densities were much lower. This delay could also have provoked a significant depletion of soil seed bank due to the emergence of seedlings before sowing (Gill and Holmes 1997). Moreover, in the WB–chemical system, with 3 months delayed seeding, this seed bank depletion could have been higher, with 4 seedlings m^{-2} the second season and 132 seedlings m^{-2} the fourth from November until the delayed seeding in January. This delay reduced the weed levels after the sowing, but it could also have allowed a more efficient control later in the season because weeds were smaller and, thus, more sensitive to herbicides (Kudsk and Streibig 2003). Besides, delay of the sowing date could have reduced *P. rhoeas* seed production of surviving plants at the end of the growing season, as late emerging cohorts of *P. rhoeas* competing with cereals show lower fecundity levels than early emerging ones (Torra and Recasens 2008).

Some studies have demonstrated that harrowing alone is not sufficient to control herbicide resistant *P. rhoeas* at high infestations levels (Cirujeda et al. 2003). In this experiment, very good controls were achieved during three seasons in systems with mechanical control by harrowing. A 2-week sowing delay combined with mechanical control showed that very effective control of herbicide resistant *P. rhoeas* is possible, probably because a reduction of *P. rhoeas* size at treatment was achieved, thus providing very good controls.

A previous study indicated that, for *P. rhoeas* and other tap-rooted weed species, harrowing should be carried out as soon as possible (Cirujeda and Taberner 2006), when plants are still small.

3.3 Yield data

No significant differences were observed in the yields of the various systems in 2002–2003 and in 2003–2004. In 2005–2006, the highest yields (2,213–2,356 kg/ha) were obtained in the four systems that had a fallow year 3 years ago and the lowest yields (1,820–1,986 kg/ha) were in the two cereal monocultures, particularly in continuous wheat (1,820 kg/ha). No significant differences were found between individual systems with the same type of rotation (Table 3). In addition, in this trial no yield penalties were observed in the non-chemical systems with a single harrow pass, as other authors observed in semi-arid conditions in North-Eastern Spain (Pardo et al. 2008).

It has been shown, in the absence of weeds, that a sowing delay reduces cereal yields in rain-fed cropping systems because the crop cannot reach the optimal or potential development in a shorter growing period (Spink et al. 2005). However, other studies show that short sowing delays can avoid autumn–winter annual weeds' competition, thus obtaining higher yields (Singh et al. 1995). The differences found between the fallow systems and the W–chemical system the last season could be due to the presence of barley in first ones compared to wheat in the second. On the other, higher barley yields were observed for fallow systems compared to WB–chemical system. It is well known that fallow can increase organic carbon and recover soil fertility (Landgraf 2001), so the effect of fallow 3 years ago on barley yield cannot completely be excluded.

4 Conclusion

In the management of herbicide resistant *P. rhoeas* populations, different strategies can be incorporated. The incorporation of a fallow year may result in 34–78% reduction of weed density. The management of this fallow is possible without herbicides (i.e. by using ploughing or chisel cultivation) and with the same results. On the other hand, the delay of crop sowing seems to be a significant factor in reducing the weed density without yield penalties. The use of cereal varieties of short cycle or adapted to a sowing delay can favour even more the soil seed depletion. So, management of herbicide resistant *P. rhoeas* with non-chemical strategies is possible, avoiding an excessive dependence on herbicides.

In last decades, there were calls by weed and agricultural scientists to develop theoretical frameworks that more fully integrate ecology with agricultural production, to reduce the need for external agricultural inputs and develop more sustainable agroecosystems (Liebman and Davis 2000; Mortensen et al. 2000). However, this has not yet been achieved (Zimdahl 2004) and the transformation of practices towards less intensive systems is still required. This study shows that there are control strategies to manage herbicide resistant *P. rhoeas* populations that can meet these principles.

Table 3 Cereal yields in kg/ha (±SE) for six management systems during four seasons

Type	Management system	Crop rotations	2002–2003	2003–2004	2004–2005	2005–2006
Chemical	W–chemical	W–W	2,341±125 a	3,151±287 a	–	1,820±147 d
	WB–chemical	W–B with delayed seeding	2,548±81 a	4,093±105* ab	–	1,986±96* cd
	FWWB–persistent	Fallow with persistent herbicide–W–W–B	–	3,233±173 a	–	2,113±59* abc
	FWWB– no persistent	Fallow with non-persistent herbicide–W–W–B	–	3,373±134 ab	–	2,290±36* ab
Non-chemical	FWWB–chisel	Fallow with harrowing and chisel–W–W–B	–	2,954±372 a	–	2,183±64* abc
	FWWB–mouldboard	Fallow with ploughing–W–W–B	–	2,968±300 a	–	2,356±48* a

In 2004–2005 wheat was not possible to harvest due to a severe drought. If not indicated, wheat (W) was sown; when indicated with asterisk, barley (B) was sown. Values within season with the same lowercase letters are not significantly different based on LSD's test ($\alpha \leq 0.05$)

W–chemical wheat monocrop with chemical control, *WB–chemical* wheat–barley with delayed seeding in January with chemical control, *FWWB–persistent* fallow with persistent herbicide–wheat–wheat–barley with chemical control, *FWWB–non-persistent* fallow with non-persistent herbicide–wheat–wheat–barley with chemical control, *FWWB–chisel* fallow with harrowing and cultivation–wheat–wheat–barley with harrowing, *FWWB–mouldboard* fallow with mouldboard ploughing–wheat–wheat–barley with harrowing

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