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PIM (Poppy Integrated Management): a bio-economic decision support model for the management of *Papaver rhoeas* in rain-fed cropping systems

J TORRA*, A CIRUJEDA†, J RECASENS*, A TABERNER*‡ & S B POWLES§

**Departament d'Hortofructicultura, Botànica i Jardineria, ETSEA, Universitat de Lleida, Lleida, Spain, †Unidad de Sanidad Vegetal, CITA, Diputación General de Aragón, Zaragoza, Spain, ‡Servei de Sanitat Vegetal, Unitat de Malherbologia, Departament d'Agricultura, Ramaderia i Pesca, Generalitat de Catalunya, Lleida, Spain, and §Western Australian Herbicide Resistance Initiative, School of Plant Biology, University of Western Australia, Crawley, Perth, WA, Australia*

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Summary

A bio-economic model for *Papaver rhoeas* designed for dry-land cropping systems in Spain was developed. The model included four seed bank layers to simulate seed movement in the soil profile resulting from tillage, with different emergence rates and seed bank mortalities depending on soil cultivation and burial depth. Users of Poppy Integrated Management (PIM) might specify the crop sequence and any feasible combination of 38 different weed management practices (herbicide and non-herbicide options) each year over 10 or 20 years. Weed treatment options included selective herbicides (14), non-selective herbicides (1), non-herbicide treatments (11) and user-defined treatments (1). PIM represented weed and seed bank population dynamics, weed–crop competition, weed treatment impacts, agronomic practices and financial details. The bio-economic model could be used to evaluate weed management scenarios by investigating the implications of different tillage, fallow and cereal rotational sequences and of constraints on herbicide availability. Model validation combined available data from literature with our own data, to show that PIM was sufficiently accurate for predicting *P. rhoeas* population dynamics. Sensitivity analyses indicated that economics associated with fuel, fertiliser and seed costs, as well as grain yield and price, were primary drivers of management decisions, whereas seedling emergence and initial seed bank size were of secondary importance.

Keywords: modelling, weed–crop competition, cereals, herbicide resistance, integrated weed management, tillage, common poppy.

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Introduction

Cereals are the most important crop in dry-land areas of Southern Europe. In Spain, nearly 6 million ha of winter cereals are sown each year (MAPA, 2006). A common practice in the past in the drier areas, before the availability of herbicides, was to alternate years of crop with fallow and to cultivate the fallow to control weed populations. The use of herbicides together with mechanisation began in the 1950s and practices such as ploughing, fallowing and mechanical weed control diminished. In the drier areas, the most common soil tillage practice in recent decades has been minimum tillage, which includes a single pass with a narrow-tined implement with minimal (25%) soil disturbance associated with seeding. Nevertheless, zero tillage is being

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Correspondence: J Torra, Departament d' Hortofructicultura, Botànica i Jardineria. ETSEA, Universitat de Lleida. Rovira Roure 191, 25198 Lleida, Spain. Tel: (+34) 973702549; Fax: (+34) 973238264; E-mail: joel@hbj.udl.es

adopted in some areas to reduce costs and soil degradation and very few farmers plough the soil. In contrast, ploughing is still a common practice in wetter areas of the north of Spain. Weed control in these areas consists almost exclusively of herbicide use, frequently a single post-emergent tank mix of herbicides controlling dicotyledon and grass weeds sprayed between November and March. Moreover, alternation of herbicides from year to year is not common.

In these conditions, *Papaver rhoeas* L. (common poppy), is the most important dicotyledon weed species infesting winter cereals in north-eastern Spain. Because of high seed production, highly persistent seeds and an extended period of germination, *P. rhoeas* is difficult to control, and it is also a competitive weed that can substantially reduce grain yields (Mcnaughton & Harper, 1964; Wilson *et al.*, 1995; Cirujeda *et al.*, 2006). Control became worse with the appearance of herbicide resistant biotypes. Poor control of *P. rhoeas* in Spain using 2,4-D was reported in 1992 (Taberner *et al.*, 1992) and the first multi-resistant population to 2,4-D and tribenuron was documented in 1998 (Claude *et al.*, 1998). Since then, farmers became increasingly concerned about herbicide resistant poppy. In a survey conducted in north-eastern Spain between 1990 and 2001, where 134 populations were sampled, 85% were found to be resistant to 2,4-D and 72% to tribenuron-methyl to some extent (Cirujeda, 2001).

Currently, farmers are not able to achieve good control of herbicide resistant *P. rhoeas* using herbicides alone, so the introduction of alternative techniques, integrating herbicide and non-herbicide tactics is required (Mortensen *et al.*, 2000). However, developing integrated weed management (IWM) programmes that incorporate all these possibilities, i.e. harrowing, delayed sowing, fallowing, ploughing, crop rotation, etc., requires both a full knowledge of the species' life cycle and a good understanding of the effects of the control methods on short and long term population dynamics. Furthermore, the design and testing of regionally specific IWM strategies presents a major challenge (Powles & Bowran, 2000).

The few studies on *P. rhoeas* biology and management in Mediterranean climates give limited insight into the long-term effects of management practices. Traditionally, the main method to demonstrate the benefits of IWM has been field experimentation, but this is impractical in the case of a large number of possible weed management combinations and the spatial and temporal complexities that must be appraised (Jones & Medd, 2005). An alternative approach is to use mathematical modelling to evaluate the effect of particular technologies and IWM combinations on weeds. Population dynamics models, based on experimental data on the annual life-cycle of weeds in cereal crops, have been used to investigate the effects of different management strategies (Cousens & Mortimer, 1995). In the case of *P. rhoeas*, modelling has not been used to explore the consequences of various control strategies. However, some studies have analysed weed–crop competition effects on weed biomass, weed seed production and wheat yield (Lintell-Smith *et al.*, 1991; Wilson *et al.*, 1995), but competition under different management scenarios has not been studied. Furthermore, until now, there has been no economic analysis on *P. rhoeas* which considers the integration of different control options and determines an optimal set of decision rules under Mediterranean conditions.

Bio-economic models of crop production systems have been developed to assess management strategies for irrigation scheduling, insect pest management, weed management, soil fertility management and field time management (King *et al.*, 1993). Economic research on the management of herbicide resistant weeds has been also undertaken (Pannell & Zilberman, 2001). As the complexity of weed management increases, more information must be integrated to make the best weed control decisions possible. This requires a wide array of information, including weed biology, crop yield potential, efficacy of herbicides and mechanical control practices, economics, labour requirements, environmental risks and other factors (Buhler *et al.*, 1996). While in the last 20 years the number of bio-economic models for weeds has increased (Goddard *et al.*, 1995; De Buck *et al.*, 1999; Monjardino *et al.*, 2003; Mullen *et al.*, 2003; Pannell *et al.*, 2004), few of them have taken into account different tillage practices and their effects on population dynamics of herbicide resistant weeds in winter cereals in Mediterranean conditions.

The objectives of this paper are to describe the Poppy Integrated Management (PIM) model developed for *P. rhoeas* management in Spanish winter cereals for dryland areas under Mediterranean conditions. We illustrate its potential use to simulate *P. rhoeas* population dynamics through a validation test and perform a sensitivity analysis of model parameters. We present an overview of the model development and a description of the biological, agronomic and economic components, focusing specifically on biological parameters.

Materials and methods

Model description

PIM is a bio-economic model that simulates the population dynamics of *P. rhoeas* over a 20 year period within a single cereal field. The model is deterministic and does not include stochastic elements, like weather.

PIM integrates biological, agronomic and economic components. It is based on previous models developed for ryegrass and wild radish management (RIM and Multispecies RIM) in a Western Australian cropping system designed as research and decision support tools (Monjardino *et al*., 2003; Pannell *et al*., 2004). This version is an experimental tool designed for the evaluation of various IWM programmes to control herbicide resistant *P. rhoeas*. The model includes approximately 400 parameters, which represent the biology of *P. rhoeas* and two cereals (barley and wheat), weed–crop competition, as well as the economics of agricultural production and management (prices, farming costs, etc.), with different tillage systems including fallows, and agronomic aspects (herbicide efficacies, phytotoxicities, etc.). As a decision tool, the user will normally 'play' or 'change' few of the parameters. Modelling with much simpler models for *P. rhoeas* IWM has been done before (Torra *et al*., 2008), but they are not useful as a decision tool for specific situations or fields. The outputs of the model are weed and seed bank density, cereal yield and profit.

Model development

Population dynamics

The year is divided into nine periods based on timing of the control treatments, tillage operations and sowing dates (Table 1, number 1 to 9). The model operates biologically at the level of these time steps, rather than on a daily or weekly time step. This was judged to be a suitable compromise between detail and practicality.

Above-ground weed numbers (m^{-2}) and weed seed numbers (m^{-2}) in the soil are recorded at the end of each of the periods. Factors influencing these numbers include: initial seed bank density, timing of emergence relative to the crop, tillage operations, natural mortality of plants and seeds, seed production per plant, impacts of weed and crop densities on seed production per plant, effectiveness of treatments to reduce weeds or seeds, etc.

In this version, some modifications were made compared with previous models, based on the biology of *P. rhoeas* and Spanish agronomic practices. Table 1 summarises the default values of the key model parameters driving the dynamics of the weed populations over time.

Effects of tillage systems on seed bank and emergence

The seed bank refers to *P. rhoeas* seeds present in the top 20 cm of soil, which is the conventional ploughing depth in Spanish cereal fields. The tillage operations available for Spanish farmers are mouldboard ploughing, chisel cultivation and zero tillage. Thus, this model needed to simulate seed movement in the soil profile, associated with these different soil tillage systems. The vertical seed movement is simulated using the model of Cousens and Moss (1990), and later modified by Colbach *et al*. (2000), which separated the top 20 cm of soil into four layers, each of 5-cm depth, as in other modelling studies (e.g. Vidotto *et al*., 2001). The model uses probability

Table 1 PIM parameters associated with population dynamics of *Papaver rhoeas* and tillage systems

Biological variables	Tillage	Zero tillage
Total % emergence during growing season*	8.4	4.2
1. % Emergence from the beginning of season until first tillage option	0.8	0.3
2. % Emergence from first tillage prior until opening rains (sowing date)	3.2	2.2
3. % Emergence from 0 to 20 days after seeding (DAS)	1.6	0.9
4. % Emergence from 20 to 60 DAS	1.7	0.6
5. % Emergence from 60 DAS until first treatment control	0.6	0.1
6. % Emergence from first treatment until second treatment	0.2	0.03
7. % Emergence from second treatment until fallow treatment in April	0.1	0.01
8. % Emergence after fallow treatment in April until harvest	0.1	0.01
9. % Emergence harvest until beginning of next season	0.0	0.0
Natural mortality of dormant seeds 0–5 cm (%) during season	18	7
Natural mortality of dormant seeds 5–10 cm (%) during season	11	4
Natural mortality of dormant seeds 10–15 cm (%) during season	13	5
Natural mortality of dormant seeds 15–20 cm (%) during season	15	6
	No differences between tillage systems	
Losses of seeds ('fresh seeds') over summer (%)	60	
Natural mortality of seedlings (% of total seedlings)	41	
Natural mortality (% of total seedlings) for late cohorts	97	

*The values for total emergence do not match with the total of 1 to 9. This is because of rounding errors. They apply to the 0–5 cm and 5–10 cm soil layers.

matrices of seed movement from one layer to another as a result of tillage operations (see Appendix, Figure S1). Multiplication of this matrix by the number of seeds present in each layer, gives the vector of seeds present after tillage. That is:

$$\begin{pmatrix} P_{1,1} & P_{2,1} & P_{3,1} & P_{4,1} \\ P_{1,2} & P_{2,2} & P_{3,2} & P_{4,2} \\ P_{1,3} & P_{2,3} & P_{3,3} & P_{4,3} \\ P_{1,4} & P_{2,4} & P_{3,4} & P_{4,4} \end{pmatrix} \begin{pmatrix} S_{1,t} \\ S_{2,t} \\ S_{3,t} \\ S_{4,t} \end{pmatrix} = \begin{pmatrix} S_{1,t+1} \\ S_{2,t+1} \\ S_{3,t+1} \\ S_{4,t+1} \end{pmatrix}$$

where P_{ij}, is the probability of moving from the *i*th to the *j*th level, $S_{i,t}$, is the number of seeds present in layer *i* at time *t* (before tillage) and $S_{\mathrm{i},t+1}$ is the number of seeds present in layer *i* at time $t + 1$ (after tillage).

By using the described model, the following tillage options and sowing dates are available for the user:

- Two soil tillage dates before the normal crop seeding date (60 and 30 days before) for emergence stimulation and seed bank depletion.
- Three crop seeding dates (normal seeding date or 20 or 60 days delay) with zero tillage, minimum tillage or mouldboard ploughing available.
- Tillage in the fallow year: normal cultivation or mouldboard ploughing.
- Mouldboard ploughing just after harvest, to test its ability to bury *P. rhoeas* seeds set at the end of the growing season at a depth sufficient to prevent seedling emergence the next season.

Different rates of seed bank decline for each soil layer depending on soil cultivation were based on available data (Cirujeda *et al.*, 2006). Other data exist for *P. rhoeas* seed viability after burial at three depths for cultivated versus no tillage systems (Roberts & Feast, 1972). Moreover, different emergence rates for *P. rhoeas* in cultivated versus uncultivated soil (Cirujeda *et al.*, 2008), were also incorporated into the model (Table 1).

PIM assumes that *P. rhoeas* seedlings cannot emerge from depths below 10 cm, with 95% of the seedlings emerging from the top 0–5 cm soil layer, 5% from 5 to 10 cm soil layer and no seedlings emerging from the two soil layers between 10 and 20 cm depth (Table 1). That *P. rhoeas* germination occurs at or near the soil surface is well documented. Vincent and Roberts (1977) found that *P. rhoeas* seedlings could emerge only from the top 0 to 3 cm soil depth and Froud-Williams *et al.* (1984) found the maximum depth of seedling emergence was 2 cm. Lovato and Viggiani (1974) established that seedlings of *P. rhoeas* emerged from 0 and 6 cm soil depth, with zero emergence from 6 to 12 cm soil depth.

Weed–crop competition

Crop yield depends on the relative competitive abilities of the crop versus *P. rhoeas*, and the densities of each. The competition relationship for cereal yield as a function of *P. rhoeas* density, following Cousens (1985), is shown in Eqn 1:

$$Y = m\frac{C_0 + a}{C_0}\frac{C}{a + C + (k_1 W)}M + (1 - M) \qquad (1)$$

where *Y* represents the crop yield (as a proportion of the weed-free yield) (t ha^{-1}), *m* represents maximum yield produced in the absence of competition (t ha^{-1}), C_0 is a standard crop density (plants m^{-2}), *a* represents a crop background competition factor (plants m^{-2}), *C* is the crop density (plants m^{-2}), k_1 is the competition factor of *P. rhoeas* in the crop (non-dimensional), *W* is the *P. rhoeas* density (plants m^{-2}) and *M* is the maximum portion of grain yield lost at very high weed densities (%). To estimate the parameter values, data from the UK study of Wilson *et al.* (1995) were used, as deemed appropriate (R. J. Froud-Williams, pers. comm.). The parameters used are shown in Table 2.

Biomass and seed production

The effect of crop competition on the production of *P. rhoeas* biomass is calculated in the PIM model by using an adapted version of Equation 1, where a crop competes with the considered weed species. The parameter values used to calculate *P. rhoeas* biomass production are shown in Table 2, estimated from a previous study (Wilson *et al.*, 1995). Seed production (seeds m^{-2}) is calculated from the biomass production, using data from field trials conducted for 3 years in the study area (Torra *et al.*, 2008). Figure 1 shows the relationship between these two variables and the fitted equation that predicts fecundity (m^{-2}).

This version also accounts for cohort emergence on seed production. Seed production in *P. rhoeas* is highest in those plants emerging first and decreases gradually in later-emerging plants (Torra & Recasens, 2008). In the PIM model, weed seed production by cohorts is represented by seed production indices. The number of seeds

Table 2 Parameters used in the weed–crop density equations to estimate seed production and cereal yield

Cereal yield*	Wheat	Barley
k_1	2	1.74
a	5	3
M	80	80
m	3.8	3.5
C_0	438	465
C	438	490
Weed biomass production		
k_1	21	
a	22	
m	1209	

*Parameters for the Eqn 1.

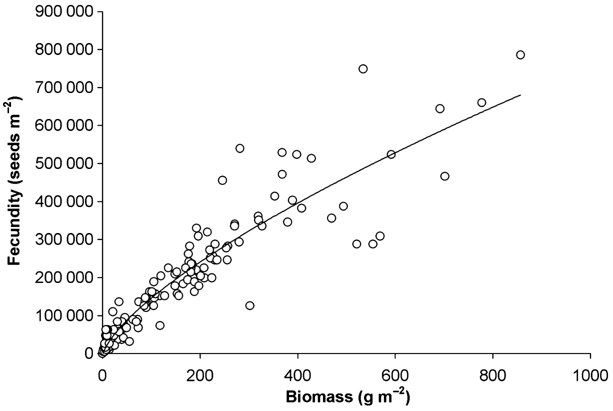

Fig. 1 Relation between biomass production (g m^{-2}) and fecundity (seeds m^{-2}) in *Papaver rhoeas* in field trials conducted during three years in the north-east of Spain. Curve equation: $Y = 850000\ (1 - e^{-0.0018x})$, $R^2 = 93$.

produced in the first four cohorts (stages 1 to 4 in Table 1) is considered the maximum seed production (100%) for *P. rhoeas*. Relative to these cohorts, the fifth and sixth cohorts (stages 5 and 6 in Table 1) produce 50% as much seed, and the last two cohorts (stages 7 and 8 in Table 1) produce 8% as much seed as the first cohorts. The sub-lethal effect of herbicides on *P. rhoeas* plants is considered as a 33% reduction of the seed production (Pannell *et al.*, 2004).

Crops

At present, the PIM model includes only two different possible crop options: wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.), together with a fallow year. No other crops are considered because of the limited rainfall (near 350 mm) which restricts crop choice. The sequence of cereals and fallow over time can be specified by the user in the model. Upon this selection, the model calculates the economics of grain production, taking into account yield loss related to (i) weed density, (ii) delayed cereal seeding, (iii) phytotoxic damage by herbicides applied during the cropping cycle or (iv) through mechanical control.

Weed control

In the PIM model, 27 herbicide and non-herbicide control options are available: 14 selective herbicides, including pre-emergence, early and late post-emergence herbicides and three mixes, which provide *P. rhoeas* control, one control option using non-selective herbicides, 11 non-herbicide methods, including cultivation, mouldboard ploughing, delayed seeding and mechanical control with a flexible tine harrow and finally one user-defined option (Table 3). To define this option, the user must enter its cost and kill rate. By default it is given a kill rate of 0 and a cost of \$0 per hectare. This option gives flexibility, for example to add new herbicides not included in the model. Grass herbicides were included as a fixed farmer cost every year (20 € ha^{-1}).

Each control strategy has its own specific impact on weed mortality and seed production (Table 3). Because control methods are conducted at different times, their combined impacts on weed densities are considered to be multiplicative, rather than additive (Pannell *et al.*, 2004).

While the PIM model is not a resistance model (as it does not include the genetics of resistance), it includes the possibility to specify the herbicide resistance status of *P. rhoeas* with respect to each of eight herbicide mode of actions (Heap, 2008) shown in Table 3. The resistance status for an herbicide group was defined as the remaining number of applications from that group before the start of full resistance. It was assumed that each application of herbicide mixtures changes the resistance status by only one-half of a unit for each constituent herbicide in the mixture, compared with one unit for herbicides applied individually.

Limited data made it difficult to estimate the number of herbicide treatments that *P. rhoeas* would need to evolve resistance for each mode of action. However, it is known that *P. rhoeas* can evolve resistance quite quickly (five applications) to herbicides in groups B and I (M. Sattin, pers. comm.). For the other herbicides, ten treatments were considered sufficient.

Economic values

PIM allows users to examine long-term benefits despite short-term economic sacrifices, calculating costs, revenues, profit on an annual basis, and net present value (NPV). PIM also includes more complex parameters such as tax and long-term trends on prices and yields. Costs associated with cropping and various weed control options have been calculated in detail, accounting for costs of input purchases, machinery operation, maintenance, repayment and crop insurance. Other costs are crop yield losses due to practices such as delayed seeding date or mechanical control. Economic returns from crops are based on grain sale prices (Generalitat de Catalunya, 2008). Following Goddard *et al.* (1996), annual net profit from cropping for 1 ha is given by:

$$R = P_W Y - C_n - C_h - C_f \qquad (2)$$

where R is the annual net profit, P_W is the crop sale price (€ t^{-1}), Y is the crop yield (t ha^{-1}), C_n is the cost of non-herbicide control (€ ha^{-1}), C_h is the cost of herbicides (€ ha^{-1}) and C_f is the fixed costs (e.g. fertilisers and seeding, in € ha^{-1}).

Annual net profits must be discounted to make them comparable with the beginning of the period, because the model can be run for 20 years. For this purpose,

Table 3 Weed control methods and effectiveness included in the PIM model for *Papaver rhoeas*. The letters indicate the crop to which the method is applicable

Type	Herbicide group	Weed control methods	Crops	% of weed control
Non-selective herbicides	G	Glyphosate	W, B, F	99
Selective herbicides				
Pre-emergence	K1	Pendimethalin	W, B	99
	K1 + C2	Pendimethalin + linuron	W, B, F	98
Early post-emergence	F1 + C2	Beflubutamide + isoproturon	W, B	95
	B	Tribenuron-methyl	W, B	87
	C3 + C3 + O	Ioxynil + bromoxynil + mecoprop-P	W, B	99
	B + O	Florasulam + 2,4-D	W, B	95
	E + C2	Pyraflufen-ethyl + isoproturon	W, B	91
	C2 + F1	Isoproturon + diflufenican	W, B	92
	B + C1	Tribenuron-methyl + metribuzin	W, B	94
	O + F1	MCPA + diflufenican	W, B	91
Late post-emergence	C3 + C3 + O	Ioxynil + bromoxynil + mecoprop-P	W, B, F	84–95
	O	2,4-D	W, B	50*
	C3 + O	Bromoxynil + 2,4-D	W, B	96
	B + O	Florasulam + 2,4-D	W, B	82
Non-chemical methods		Early mechanical control	W, B, F	85
		Late mechanical control	W, B, F	79
		High crop seeding rate	W, B	–†
		Cultivation 60 days before seeding	W, B, F	99
		Mouldboard ploughing 60 days before seeding	W, B, F	100
		Cultivation 30 days before seeding	W, B, F	99
		Mouldboard ploughing 30 days before seeding	W, B, F	100
		Seed at opening rains‡	W, B	99
		Wait 20 days, seed‡	W, B	99
		Wait 60 days, seed‡	W, B	99
		Mouldboard ploughing just after harvest	W, B, F	100
		User-defined option	W, B, F	–§

W, wheat; B, barley; F, fallow; MCPA, 2,4-methylchlorophenoxy acetic acid.
*Assuming that the population is 2,4-D resistant.
†No fixed value, depends on weed and crop densities and on relative competitiveness of weeds and crops.
‡In each sowing date three tillage options are available: direct drilling, minimum tillage, and ploughing.
§Defined by the user.

a real discount rate (r) of 8% per year is used. The sum of discounted net profits gives the NPV:

$$NPV = \sum_{t=1}^{T} \frac{P_W Y - C_n - C_h - C_f}{(1+r)^t} \tag{3}$$

While the model does not optimise benefits, it can be used to simulate a wide range of potential treatment strategies, so that an overall strategy, which is at least near optimal, can be identified.

Model validation

The validation approach undertaken was a comparison between PIM predicted and observed values of seed bank at the beginning of the season (n = 25) and mature plant densities at the end of the season (n = 34), using collected field data (Torra *et al.*, 2008) and data in the literature on Spanish cereals (Dorado *et al.*, 1999). This was done for a one life-cycle situation, assuming that 75% of seeds were in the 0–5 cm soil layer and 25% in the 5–10 cm layer for observed values. Model performance was evaluated with a simple linear regression analysis between observed and predicted values for seed bank and mature plant densities, respectively. In both cases, separate data sets were analysed for different tillage systems, ploughing (n = 19 for seed bank and n = 7 mature plants) and minimum tillage (n = 6 for seed bank and n = 28 for mature plants), and separate data sets for different types of weed control, chemical with herbicides (n = 16 for seed bank and n = 24 for mature plants) and mechanical control by harrowing (n = 9 for seed bank and n = 12 for mature plants). Moreover, the intercept and the slope from each regression equation were compared to zero and one, respectively, to test the accuracy of predictions.

In all situations for the observed values, the seed bank (0 to 10 cm layer) was assessed prior to seedbed preparation and after crop harvest. For zero tillage, only one seed bank data set was available (Dorado *et al.*,

1999) and linear regression was not possible. Nevertheless, the prediction from the model (100 seeds m^{-2}) was in the range of the observed value (72 seeds m^{-2}).

Sensitivity analysis

Sensitivity analysis was used to explore changes in parameter values. The overall approach is consistent with Pannell's (1997) Strategy C for sensitivity analysis. The selection of the parameters and their value ranges for the sensitivity analysis was based on previous studies (Monjardino *et al*., 2003). In this study, a broad range of uncertain parameters was evaluated. These included crop-related parameters (e.g. weed-free yield, yield penalties and herbicide phytotoxicities), weed-related parameters (e.g. initial seed densities, annual seed bank decline, mortality, seed production and competitiveness), efficacies of several control practices, tillage parameters, and economic parameters (e.g. net sale prices of cereals, seed prices, herbicide prices, diesel price and discount rate). A list of the 28 selected uncertain parameters and their value ranges (minimum, standard, and maximum) is shown in Table 4.

On the basis of the range of values defined for each parameter, a sensitivity index (I) was calculated, to provide information about the relative sensitivity of the results to that parameter:

$$I = (P_{\max} - P_{\min})/P_{\text{st}} \tag{4}$$

where $P_{\max}$ represents the annual equivalent profit of the weed management strategy when the parameter in question is set at its maximum value, $P_{\min}$ is the annual equivalent profit given the minimum value and P_{st} is the annual equivalent profit for the standard value. This was done for two weed management scenarios with the same initial *P. rhoeas* seed distribution (densities of 2500 (0–5 cm), 1000 (5–10 cm), 50 (10–15 cm), and 50 (15–20 cm) seeds m^{-2}): (i) a wheat–wheat–barley rotation with zero tillage and one glyphosate and one post-emergence herbicide application per year (groups B, C, F, G and I) and (ii) a wheat–wheat–barley rotation with minimum tillage and one post-emergence herbicide application per year (same previous herbicides). The index was calculated for both scenarios and parameters were ranked according to the average (Table 4).

Simulations

To illustrate the use of PIM to evaluate weed management alternatives, a comparison of different tillage systems for *P. rhoeas* management (zero tillage, minimum tillage, mouldboard ploughing and combined tillage) are shown. No constraints are placed on the use of non-selective herbicides or non-chemical treatments, other than those that are required agriculturally. Simulations are based on one of the most typical scenarios in the winter cereals: a barley-barley-barley-wheat rotation and one post-emergence herbicide application per year (rotation of the herbicides bromoxynil + ioxynil + mecoprop-P and MCPA + diflufenican). The population was assumed to have multiple resistance to group B herbicides (tribenuron-methyl) and group O herbicides (2,4-D), a common situation, so that herbicides from groups B and O are not available. Ten treatments were available from the remaining herbicide groups for selective herbicides, and 20 for non-selective herbicides. Initial seed bank densities were 2500 seeds m^{-2} (0–5 cm), 1000 seeds m^{-2} (5–10 cm), 500 seeds m^{-2} for 10–15 cm and 15–20 cm layers. These numbers reflect a typical infestation with *P. rhoeas* of 3500 seeds m^{-2} (Izquierdo & Recasens, 1990; Torra, 2007), and the densities for the four soil layers were deduced from this value. The details of the strategies adopted in the simulated scenarios are shown in Table 5.

Results

Model validation

The simple linear regression between the predicted and observed seed bank numbers at the beginning of the season were significant ($P < 0.01$) and R^2 higher than 0.95 for all data sets (Fig. 2). The intercept was statistically different from zero and the slope from one only in the ploughing case (Table 6), indicating underestimation for high observed values and overestimation for low values.

For mature plants densities at the end of the growing season, simple linear regressions were significant ($P < 0.01$) and R^2 higher than 0.9, being slightly lower (0.74) for the herbicide data set (Fig. 3). The intercept was statistically different from zero for all data sets and the slope was not statistically different from one only for the minimum tillage data set (Table 6). For minimum tillage, PIM was always overestimating the plant density values (Fig. 3), but differences were small and the slope was not different from one. For the herbicides estimations, the model was overestimating at very low observed densities. For ploughing and harrowing data sets, PIM was underestimating at very high observed densities and overestimating at very low densities (intercept and slope different from zero and one, respectively, Table 6).

Sensitivity analysis

The ranking of the sensitivity indices allowed the selection of the most important parameters (Table 4). Parameters were grouped into those with an absolute

Table 4 Values and sensitivity index results for the parameters included in the model (model default values in bold) for a tillage and a zero tillage scenarios for *Papaver rhoeas*. Most significant parameters above the dashed line

Parameters	Min. value	Stand. value	Max. value	Index for tillage	Index for zero tillage	Average*
Weed-free wheat yield (t/ha)	2.5	**3.8**	6	1.498	1.332	1.415
Net wheat sale price (€/t)	162	**220**	255	0.858	0.763	0.811
Weed-free barley yield (t/ha)	1.8	**3.3**	5	0.587	0.521	0.554
Price of superphosphate	90	**190**	300	−0.329	−0.292	−0.311
Net barley sale price (€/t)	138	**200**	230	0.300	0.267	0.283
Price of urea	262	**409**	600	−0.265	−0.235	−0.250
Cost of diesel (€/l)	0.4	**0.8**	1.2	−0.242	−0.066	−0.154
Cost of cereal seeds (€/ha)	25	**43**	60	−0.137	−0.122	−0.129
Phytotoxicities of selective herbicides (%)†	–	–	–	−0.032	−0.029	−0.030
P. rhoeas annual emergence (%)						
Tillage	0	**8.35**	31	−0.042		−0.030†
Zero tillage	0	**4.2**	15		−0.018	
Price of glyphosate (€/l)	4.0	**6.8**	15.0	−0.000	−0.057	−0.029
P. rhoeas initial seed density: 0–5 cm (seeds/m^2)	0	2500	10000	−0.031	−0.024	−0.028
Standard crop density C_0 – wheat	250	**438**	500	−0.015	−0.014	−0.014
Prices of selective herbicides (€/l)†	–	–	–	−0.014	−0.010	−0.012
Control efficacies of selective herbicides (%)†	–	–	–	0.012	0.007	0.010
P. rhoeas seedling mortality first treatment for wheat	15	**34**	80	0.010	0.006	0.008
Natural mortality of seeds during season 0–5 cm	5	**18**	64	0.011	0.004	0.007
P. rhoeas initial seed density: 5–10 cm (seeds/m^2)	0	**1000**	5000	0.011	0.001	0.006
Inter-weed competition – B – seed production	0.001	**0.002**	0.01	0.007	0.004	0.005
Max yield lost to *P. rhoeas* at high density	50	**80**	95	−0.006	−0.004	−0.005
P. rhoeas mortality over summer (%)	0	**60**	99	−0.006	−0.003	−0.005
k – (parameter for wheat yield)	1.5	**2**	2.5	0.005	0.003	0.004
Standard crop density C_0 – barley	270	**465**	500	−0.002	−0.002	−0.002
m – (parameter for biomass production)	200	**1209**	1500	−0.002	−0.001	−0.002
K – (parameter for biomass production)	13	**21**	30	−0.002	−0.001	−0.002
Inter-weed competition - A - seed production	350 000	**850 000**	1 000 000	0.001	0.001	0.001
Natural mortality of seeds during season 5–10 cm	6	**11**	16	−0.001	<−0.001	−0.001

*Average between tillage and non-tillage scenarios.

†Mean between individual sensitivity indices for each selective herbicide.

Table 5 Simulation results and details for an herbicide resistant *Papaver rhoeas* population (groups B and O) over 10 years for a wheat–barley–barley–barley rotation under four different tillage scenarios to be compared

	Zero tillage	Minimum tillage	Mouldboard ploughing	Mixed scenario
Total use of selective herbicides				
Post emergence herbicides	10[*]	10[*]	10[*]	7[*]
Pre emergence herbicides	0	0	0	3†
Total uses of tillage operations				
Mouldboard ploughing before sowing	0	0	10	1‡
Mechanical control	0	0	0	0
Non-selective herbicides	10	0	0	5§
Minimum tillage	0	10	10	3†
Direct drilling	10	0	0	7
Average *P. rhoeas* density (plants m^{-2})	0.6	0.9	0.4	0.3
Seed bank density 0–10 cm depth (seeds m^{-2})	1472	524	469	593
Equivalent annual profit (€ ha^{-1})	282	248	195	262

[*] Bromoxynil + ioxynil + mecoprop-P at 150 + 150 + 450 g a.i. ha^{-1} or MCPA + diflufenican at 500 + 50 at g a.i. ha^{-1}.

†Pendimethalin + linuron at 990 + 84 g a.i. ha^{-1} with minimum tillage in years 2,3 and 6.

‡Second year.

§Years 1, 4, 5, 9 and 10.

sensitivity index value equal to or greater than 0.1. This corresponded with a significant impact on the outcome of the model (at least 1 € ha^{-1} for 20 years), therefore driving management choices. Eight parameters fitted this profile (above the dashed line, Table 4). The most important were the weed-free yield and the net

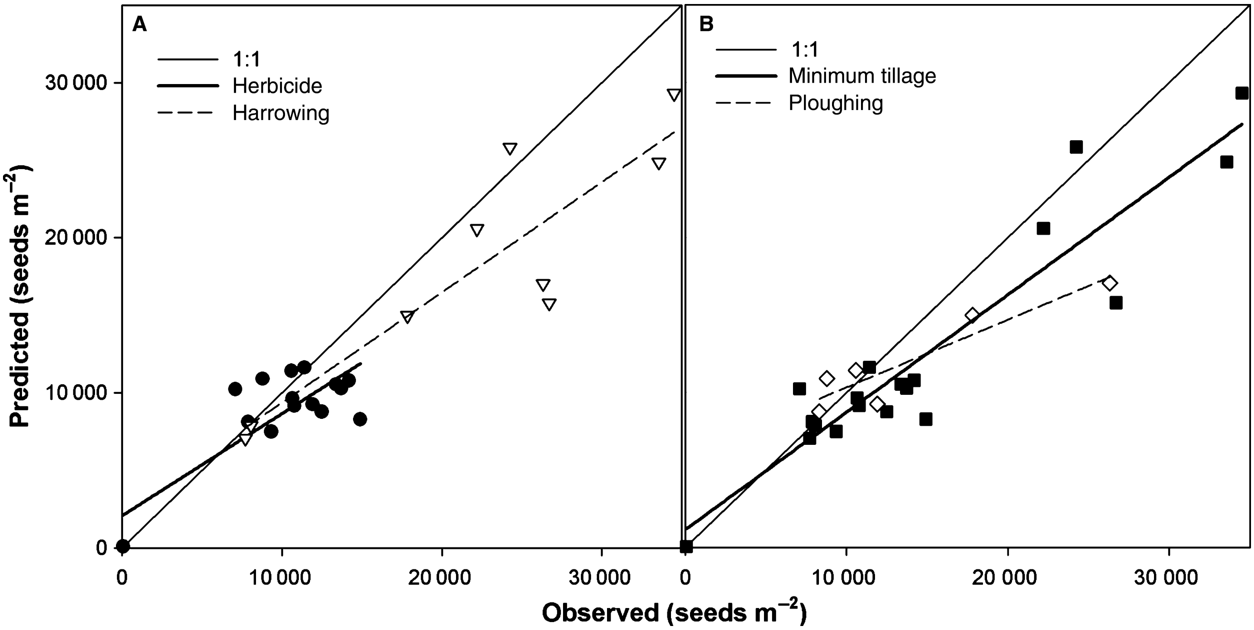

Fig. 2 Seed bank densities (0–10 cm depth) predicted by the model versus measured data regarding type of tillage and weed control for *Papaver rhoeas*. (A) Type of weed treatment: ●, herbicide, solid regression line, $y = 0.66x + 2064$, $R^2 = 0.96$; ▽, harrowing, dash regression line, $y = 0.71x + 2255$, $R^2 = 0.97$. (B) Type of tillage: ■, minimum tillage, solid regression line, $y = 0.76x + 1155$, $R^2 = 0.97$; ◇, ploughing, dash regression line, $y = 0.44x + 5970$, $R^2 = 0.97$. The 1:1 line represents a perfect agreement.

Table 6 Comparative statistics from linear regression analysis for four different estimates of seed bank densities (0–10 cm depth) and mature plant densities at the end of the growing season considering tillage system and weed control treatment in *Papaver rhoeas*

	Seed bank densities				Mature plants densities			
	Intercept		Slope		Intercept		Slope	
Studied case	Value ± SE	*P**	Value ± SE	*P*†	Value ± SE	*P**	Value ± SE	*P*†
Minimum tillage	1154 ± 1226	0.36	0.872 ± 0.07	0.06	3.323 ± 1.34	0.02	1.124 ± 0.09	0.16
Ploughing	5970 ± 1384	0.01	0.436 ± 0.09	0.01	1.880 ± 3.31	0.60	0.785 ± 0.06	0.01
Herbicide	2064 ± 1276	0.13	0.659 ± 0.12	0.08	3.404 ± 0.74	0.01	0.417 ± 0.14	0.04
Harrowing	2254 ± 3331	0.52	0.771 ± 0.14	0.06	11.18 ± 4.29	0.03	0.753 ± 0.09	0.01

*Probability of non-significant difference between the intercept value and zero.
†Probability of non-significant difference between the measured slope and one.

sale price for wheat, followed by the weed-free yield for barley, the price of superphosphate, the net sale price for barley and urea price. The model was also responsive to the costs of diesel fuel and cereal seeds. In the case of fuel price, sensitivity was correlated with the impact of cultivation costs (fuel consumption) in tillage systems. The most sensitive biological parameters were *P. rhoeas* annual emergence and the initial seed bank density at 0–5 cm depth. In other scenarios, the depth of burial can be slightly more sensitive, for example when a single ploughing is performed and assuming that the deep layers of the soil (10–15 and 15–20 cm) are empty or with very low *P. rhoeas* seed densities (data not shown).

Simulations

The highest annual profit (282 € ha^{-1}) was for the zero tillage scenario, and the lowest income (195 € ha^{-1}) for the mouldboard ploughing scenario (Table 5). After 10 years, the seed bank density (0–10 cm depth) was 1472 seeds m^{-2} for the zero tillage scenario and from 469 to 593 seeds m^{-2} for the other three scenarios. *Papaver rhoeas* density before harvest was below one plant m^{-2} in all years for all the scenarios simulated. As an example, the gross margin (€ ha^{-1} year^{-1}) and the *P. rhoeas* density before harvest (plants m^{-2} year^{-1}) over a period of 20 years for the Mixed Scenario (Table 5) are shown in Fig. 4.

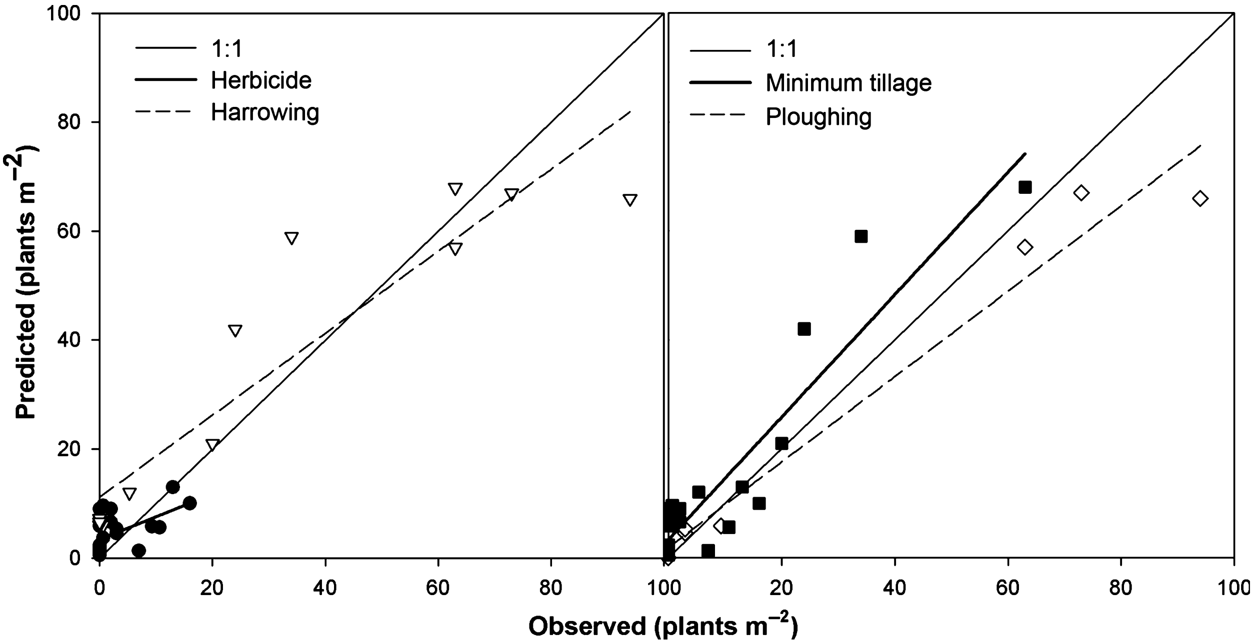

Fig. 3 Mature plant densities predicted by the model versus measured data regarding type of tillage and weed control for *Papaver rhoeas*. (A) Type of weed treatment: ●, herbicide, solid regression line, $y = 0.42x + 3.4$, $R^2 = 0.74$; ∇, harrowing, dash regression line, $y = 0.75x + 11.2$, $R^2 = 0.95$. (B) Type of tillage: ■, minimum tillage, solid regression line, $y = 1.12x + 3.3$, $R^2 = 0.91$; ◇, ploughing, dash regression line, $y = 0.78x + 1.9$, $R^2 = 0.98$. The 1:1 line represents a perfect agreement.

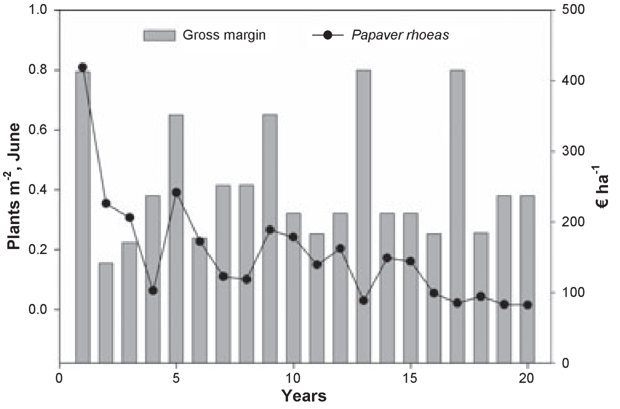

Fig. 4 Annual gross margin (€ ha^{-1}) and *Papaver rhoeas* density (plants m^{-2}) in crop before harvest over 20 years for a barley–barley–barley–wheat rotation with 20 applications of selective herbicides subjected to the control options shown in Table 6 for the Mixed scenario.

Discussion

The validation with the regression analysis showed that, overall, PIM performed well predicting seed bank densities at the beginning of the growing season (Table 6). For the ploughing predictions, the limited data set ($n = 7$), and the added difficulty of correctly estimating the seed bank densities between 10 and 20 cm depth, could explain the lower performances, with intercept and slope different from zero and one, respectively. The reason for the overestimation at low observed densities for the herbicide data set could be higher herbicide efficacies for the observed data, compared with the average efficacies used by PIM. For mature plants at the end of the growing season, lower accuracies in predictions were found and a possible density-dependent relationship for weed control efficacies could be the reason. The values predicted by PIM were in the range of the observed values for the ploughing and harrowing data sets. The range of data for the herbicide data sets (both seed bank and mature plant densities) was not sufficient.

The sensitivity analysis showed similar results to those obtained in the original model (Monjardino *et al.*, 2003). The cost related parameters (i.e. tillage operations depending on fuel cost) and profit related parameters (i.e. price and weed-free yield of cereals), were the most sensitive. For this reason, IWM strategies linked to cost related parameters and to profit related parameters would drive management decisions. Parameters were more sensitive in the tillage scenarios compared with scenarios with non-tillage. The reason is that costs in tillage scenarios are higher because of cultivation operations, resulting in lower incomes, making the annual profit more susceptible to changes in cereal yield, weed densities, etc.

As expected, the relationship between plant density and gross margin is not strong (Fig. 4), for which there are several reasons. The economic difference between years or scenarios is not due to differences in weed densities, but to differences in total weed control costs. The crop choice (wheat, barley, and fallow) has a big impact in the outcome, because prices are different between cereals (barley was cheaper than wheat at that moment) or there is no income in a fallow year. For example, depending on year, the costs of control tactics will vary with herbicide price, while fuel consumption will differ between tillage regimes.

The simulation of different scenarios showed that the annual profit increased as tillage operations were reduced and for this reason the best income was for the zero tillage scenario (Table 5). Conversely, after 10 years, seed bank density from 0 to 10 cm depth was the highest for zero tillage compared with the scenarios with tillage with faster seed bank declines (Fig. 5). Relatively quick seed bank declines have been observed in annual ploughed soils (Wilson & Lawson, 1992). Of the scenarios already simulated, three of them, zero tillage, minimum tillage and ploughing, are already practiced in Spain. There is some evidence for seed decline at this rate in 'real-life' field observations, when excellent weed control is achieved (J. Torra, pers. obs.). Because under a non-cultivated soil *P. rhoeas* emergence is lower (Cirujeda *et al.*, 2008) and costs associated to tillage operations are reduced, zero tillage with direct drilling can be an attractive solution for *P. rhoeas* management. For the minimum tillage and mouldboard ploughing scenarios, costs are increased, especially for the second one, as found in other studies (Sanchez-Giron *et al.*, 2007), but the seed bank depletion is better in ten years. For this reason, the combined scenario (7 years with zero tillage, 2 with minimum tillage and one with ploughing as detailed in Table 6) was a good compromise between profitability and *P. rhoeas* management, and a possibility for *P. rhoeas* IWM, representing an 83% seed bank reduction in ten years. With PIM and assuming 100% herbicide efficacy (zero annual fresh seed input) under minimum tillage, after 50 years the seed bank decline would reach 91%. Lutman *et al.* (2002) conducted a 7-year experiment in cereals preventing any seed return and estimated that it would take more than 50 years to achieve a 95% reduction in the *P. rhoeas* seed bank.

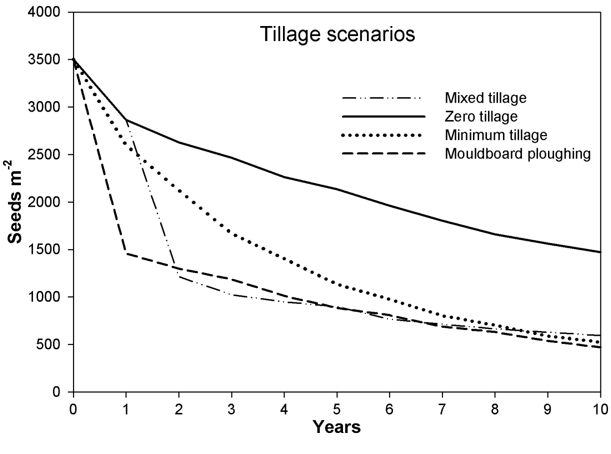

Fig. 5 *Papaver rhoeas* seed bank (0–10 cm depth) density evolution over 10 years for a barley–barley–barley–wheat rotation under four different tillage scenarios detailed in Table 6.

The Poppy IM model provided a powerful tool for evaluating the biological, agricultural and economic performance of alternative long-term weed management systems in winter cereals in Spanish dry-land areas. The validation process undertaken demonstrated the potential of PIM to predict *P. rhoeas* population dynamics. Through PIM development, research gaps in *P. rhoeas* biology and management were identified, such as the effects of tillage options on *P. rhoeas* (seed bank mortality, seed movement, emergence and seedling recruitment, related to depth), supplementary herbicide data (efficacies and phytotoxicity) and multispecies weed–crop competition between *P. rhoeas*, cereals and grass weeds. In the future, efforts will be made to collect these data and incorporate them in the model. Validation of the model is currently limited to part of *P. rhoeas* population dynamics, but a more extensive validation process is underway. Finally, a specific validation process for the profit and cereal yield outputs would be very useful. The sensitivity analyses showed that strategies linked to cost related parameters and to profit related parameters would drive management decisions. Using PIM, farmers and policy makers should realise that reducing costs and increasing incomes are the objectives, and for this reason, governments could strongly influence farmer behaviour with proper subsidy policies.

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Appendix

Appendix 1 Proportion of seeds moved from layer *i* to layer *j* by direct drilling (A), rigid tine cultivation (B) and mouldboard plough (C) in case of a seed bank divided into four 5-cm-thick horizontal layers. A and B matrices according to Cousens and Moss (1990); C matrix according to Colbach *et al.* (2000).

$$\begin{array}{ccc} \text{A} & \text{B} & \text{C} \\ \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} & \begin{pmatrix} 0.70 & 0.33 & 0.02 & 0.00 \\ 0.23 & 0.50 & 0.15 & 0.00 \\ 0.06 & 0.15 & 0.68 & 0.16 \\ 0.02 & 0.01 & 0.16 & 0.84 \end{pmatrix} & \begin{pmatrix} 0.24 & 0.24 & 0.24 & 0.24 \\ 0.26 & 0.26 & 0.26 & 0.26 \\ 0.26 & 0.26 & 0.26 & 0.26 \\ 0.24 & 0.24 & 0.24 & 0.24 \end{pmatrix} \end{array}$$