Journal of Agricultural Science (2013), **151**, 229–245. © Cambridge University Press 2012
doi:10.1017/S0021859612000159

CROPS AND SOILS RESEARCH PAPER

Using a sensitivity analysis of a weed dynamics model to develop sustainable cropping systems. I. Annual interactions between crop management techniques and biophysical field state variables

N. COLBACH* AND D. MÉZIÈRE

INRA, UMR1347 Agroécologie, ECOLDUR, BP 86510, F-21000 Dijon, France

(*Received 26 August 2011; revised 15 December 2011; accepted 9 February 2012; first published online 20 March 2012*)

SUMMARY

Environmental problems mean that herbicide applications must be drastically reduced and optimized. Models that quantify the effects of crop management techniques on weed dynamics are valuable tools for designing weed management strategies. Indeed, the techniques to be optimized are numerous and diverse, and their effects vary considerably with environmental conditions and the state of the weed flora. In the present study, a mechanistic weed dynamics model, AlomySys, was used to carry out *in silico* experiments in order to: (1) rank crop management components according to the resulting decrease in weed infestation, and (2) study the sensitivity of the major component effects to biophysical field state variables in order to identify indicators and thresholds that could serve for future decision-rules for farmers. The various results were compiled into rules for optimizing timing and other options (tillage tools, herbicide types) for the different crop management techniques. The rules were based on a series of biophysical field state variables, i.e. cumulated rainfall, thermal time, soil moisture and weed densities prior to the operation, in the previous and pre-previous crops. For instance, the first tillage should be delayed until the cumulated rainfall since harvest exceeds 50 mm and be carried out in moist conditions. Mouldboard ploughing is advised if the infestation of the previous crop exceeds 20 weeds/m^2 and particularly if this exceeds 0·3 times that of the pre-previous crop. Ploughing should occur when the cumulated rainfall since harvest reaches 100–200 mm. The effects of crop succession and long-term effects of management techniques have been studied in a companion paper (Colbach *et al*. 2012).

INTRODUCTION

Pollution of the environment (e.g. ground and surface water; IFEN 2007) by herbicides is increasing; therefore, herbicide applications must be drastically reduced and optimized. Moreover, past simplifications of crop and herbicide rotations have led to the advent of herbicide resistance in many weed species (Powles & Yu 2010), making these species more difficult and expensive to control. The recent EU directive on synthetic molecules, Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), also limited the range of herbicides available to farmers (EU 2006). Consequently, there is an increasing need for integrated cropping systems for managing weeds with little or no herbicides, basing weed control on a judicious combination of a large range of cropping system components (crop succession and the crop different management techniques). This will remain necessary even if novel weed control measures such as biocontrol, newly domesticated species or engineered weed-resistant crops become available (Gressel 2011). Indeed, changes in cropping systems and climate change are expected to lessen the efficiency and predictability of individual weed management measures (Rodenburg *et al*. 2011).

It is now well recognized that models that quantify the effects of crop management techniques on weed dynamics are valuable tools to design weed management strategies (Rossing *et al*. 1997; Aubertot *et al*. *in press*). This is particularly true when designing integrated systems where a large range of interacting

* To whom all correspondence should be addressed. Email: colbach@dijon.inra.fr

https://doi.org/10.1017/S0021859612000159 Published online by Cambridge University Press

cropping system components must be optimized. To understand and predict the variability in effects observed for given techniques and to use these models in a large range of conditions without reparametrizing, mechanistic approaches are necessary (Colbach & Debaeke 1998; Colbach *et al*. 2005; Colbach 2010). In this type of model, life-cycles are split into sub-processes depending on biological and physical effects of cropping systems, in interaction with the biological (e.g. weed stage) and physical (e.g. soil moisture) conditions. Such a model has already been tentatively used to evaluate crop rotations (Colbach *et al*. 2010*c*) and to optimize crop management techniques for controlling the harmful annual grass-weed *Alopecurus myosuroides* Huds. (blackgrass) with little or no herbicides (Colbach *et al*. 2010*b*).

These first applications have shown that the number of interesting management techniques is large. Moreover, they have revealed a large variability in weed infestation for a given scenario when tested with different weather scenarios. There are not only strong interactions between the different cropping system components, but also between these components and the biophysical conditions of the field. For instance, the efficiency of mechanical weeding has been shown to vary considerably with weed stage or soil moisture (Kurstjens & Perdok 2000; Kurstjens *et al*. 2000).

Consequently, the objective of the present paper was to carry out *in silico* experiments with AlomySys, to: (1) rank crop management components according to the resulting decrease in weed infestation and (2) study the sensitivity of the major component effects to biophysical field state variables in order to identify indicators and thresholds that could serve for future decision-rules for farmers. In order to test a large range of possible combinations of seed bank densities and crop management techniques, a global sensitivity analysis based on Monte Carlo simulations, where all input variables were made to vary randomly and simultaneously, was conducted (Saltelli *et al*. 2000). This procedure has already been used with similar models and is useful for ranking variables over a large range of situations while taking into account the interactions between the variables (Colbach *et al*. 2004; Tricault *et al*. 2009). An additional, original step of the present study consisted of studying the variability in the effects of the major crop management techniques as a function of different biophysical state variables (e.g. weed densities and soil moisture).

MATERIALS AND METHODS

The simulation model AlomySys

The AlomySys model (Colbach *et al*. 2006*a*, *b*, 2007, 2010*b*) was developed for *A. myosuroides* Huds. (blackgrass), a harmful annual grass-weed frequently found in autumn-sown crop rotations of Atlantic European countries (Van Himme & Bulcke 1975) and increasingly tolerant to various herbicides (Délye *et al*. 2007; Moss *et al*. 2007). The input variables of AlomySys consist of:

- The **daily weather** data over the simulated period consisting of rainfall, mean and minimum and maximum temperatures, as well as mean soil temperatures and water potential in successive 0·01 m thick soil layers from 0 to 0·30 m depth (the maximal depth of tillage operations).
- The **soil characteristics**, i.e. texture, gravel content and depth.
- The **initial weed infestation** characterized by the total potential emergence density in the first crop of the simulation and its timing (simultaneous with crop, continuous over cropping season, late spring).
- The **cropping system** during the whole simulated period, comprising the crop sequence, the date of all operations (tillage, sowing, herbicides, mechanical weeding, mowing, nitrogen fertilizer, manure, harvest) and their characteristics, i.e. tool, working depth and speed, etc. for tillage and mechanical weeding, active ingredient, herbicide application rate, technology and conditions, seed sowing density, nitrogen fertilizer application rate, the rate, seed and nitrogen content of manure spreading.
- The **width** of the farming equipment for tilling, sowing, spraying, hoeing etc. Increasing the width reduces soil compaction and thus pre-emergent mortality during shoot elongation from the germinated seed to soil surface.

These input variables influence the annual life-cycle of blackgrass (see Supplementary Material, available at http://journals.cambridge.org/AGS), in interaction with blackgrass stages (e.g. mortality after herbicide application depends on blackgrass stage and density), crop stages (e.g. seedling survival after emergence depends on its emergence date relative to the crop emergence date) and environmental conditions (e.g. pre-emergent seedling mortality increases with the size and compaction of soil clods as well as soil dryness). The output variables considered here are, for each simulated year, the density of emerging, surviving

https://doi.org/10.1017/S0021859612000159 Published online by Cambridge University Press

and mature plants, weed seed production and surviving seed bank at crop harvest. ALOMYSYS was evaluated with independent field observations and was shown to correctly predict seed survival, blackgrass emergence and multi-year dynamics in intensive and integrated cropping systems; in no-till systems, seed survival was overestimated though emergence was still predicted correctly (Colbach *et al*. 2006*a*, 2007).

The simulation plan

The objective of the present study was to rank crop management variables according to their effects on weed infestation in a large range of weed seed bank conditions, and to identify biophysical indicators for optimizing decision-making. The simulation plan consisted in (1) simultaneously randomizing all model input variables to obtain contrasting cropping system histories, (2) running ALOMYSYS over several years with these histories to create contrasting weed seed banks and (3) analysing the effect on weed infestation of management variables during the subsequent crop following these different weed seed banks. The crop chosen for analysing weed infestation was winter wheat, because that is the crop in which this weed species most commonly occurs. Totally 15 000 random cropping systems were run. Simulations started with 100 weed plants emerging during the first simulated crop, which was a winter wheat (to maximize initial infestation and reproduction), lasted for 20 years to maximize the difference in weed infestation between the simulated systems, and always finished with a winter wheat.

Randomization of input variables

Options for crop management variables were chosen randomly from ranges sufficiently large to comprise currently non-existing or rare, but potentially interesting, management strategies (e.g. very early sowing of summer crops to avoid summer weed emergence, cash crops sown into perennial crop cover, high-frequency tillage) as well as unusual situations resulting from organizational or climatic 'accidents' (e.g. very late crop sowing, very low crop densities or very low herbicide efficiencies). However, the possible ranges were kept realistic; for instance, winter crops could not be sown in spring, possible nitrogen fertilizer depended on crop types, etc. Details on the range and the probability for choosing options for the different crop management variables are given in the supplementary material available online (Supplementary Material). Soil characteristics and the width of farming equipment were chosen randomly at the onset of the simulation. Then, for each simulated year,

- The weather data set was chosen from a collection of 17 yearly weather sets from Dijon, France (5°2′E, 47°20′N, 220 m a.s.l.), ranging from 1988 to 2003.
- The crop (except the first and the last ones) was chosen among the 24 possible crops, comprising winter and spring cereals, legumes and other crops, temporary pasture as well as unsown setaside.
- The management techniques were chosen from options which varied with crop type. Ranges were made as large as possible but the logical ordering of operations was always satisfied (e.g. there was no tillage after sowing the crop).

Indicators for evaluating and optimizing crop management

The analysis of the simulated data consisted of two steps: (1) ranking the management variables of the analysed winter wheat as a function of weed infestation in this crop, (2) identifying and using biophysical indicators to optimize various management choices, i.e. timing and options (e.g. tools) of operations.

Ranking crop management variables

In each simulation, plants emerging before and during the analysed crop, plants surviving up to crop harvest, mature plants at crop harvest, total seed production and seed bank prior to seed rain at the harvest of the last year were kept as output variables for analysis. These variables were used to rank explanatory variables as a function of their impact on weed infestation. Explanatory variables comprised all crop management variables for the most recent simulated year as well as the weather for that year, soil texture and the seed bank at the onset of this year.

Biophysical indicators for optimizing management choices

In addition, a series of biophysical indicators were calculated during the simulations. These indicators consisted of weed (density, stage) and environmental variables (thermal time, cumulated rainfall, soil structure, soil water potential) 'observed' before management operations and, in the case of weed density indicators, during past crops. During the analysis, the variation in weed density with the various indicators

https://doi.org/10.1017/S0021859612000159 Published online by Cambridge University Press

was studied and optimal choices were identified as those minimizing weed density.

Statistical analysis

Ranking of crop management variables

Synthetic variables for each simulated year were constructed. Each year, tillage was described by 26 variables consisting of the total number of operations if no ploughing, number of operations before and after ploughing if any, number of rolling operations; the occurrence of ploughing, its width and skim-coulter characteristics (depth, width); the dates of ploughing and the first post-ploughing, those of the first and last tillage operations; the tilling depths, tractor speeds and tools at these four major dates; mean time between operations as well as mean speed and depth for all operations (Table 1*a*). The variables for describing the other operations are listed in Table 1*b*–*e*. These variables resulted into 67 management variables, increased by the weather set, the seed bank characteristics and the soil texture.

To quantify the effects of crop management variables, a linear regression was used for each of the tested output variables:

$$\begin{aligned}\text{Output variable} &= \text{constant} + \alpha \times \text{climate set} \\ &+ \sum_{i=0}^{67} \beta_i \times \text{management technique}_i \\ &+ \sum_{i=1}^{17} \chi_i \times \text{tool width}_i \\ &+ \sum_{i=1}^{22} \delta_i \times \text{seed bank characteristics}_i \\ &+ \text{soil texture effect} + \text{error} \end{aligned} \quad (1)$$

where α_i, β_i, χ_i and δ_i were regression parameters. All output densities were log10-transformed (after adding 1 to make possible the log-transformation of nil values) prior to analysis. Some of the input variables were quantitative (e.g. sowing density), other were qualitative variables (e.g. tools) and transformed into quantitative variables using boolean coding. For instance, the variable *mechanical weeding tool* with the three levels *harrow*, *hoe* and *rotary hoe* was transformed into distinct dummy variables equating (1,0,0) for harrow, (0,1,0) for hoe, and (0,0,1) for rotary hoe. The use of only quantitative variables made possible the use of the REG procedure of SAS (version 8.01), with the BACKWARD option to successively eliminate the least significant input variables from the regression model until only effects significant at a level of 0·05 remained. To illustrate the quantitative effects of the significant variables, the relative sensitivity of each weed variable to each input variable was calculated from regression parameters β_i for a given input variation:

$$\begin{aligned}\Delta_v &= \frac{\text{output}(x+v) - \text{output}(x)}{\text{output}(x)} \\ &= \frac{10^{\beta(x+v)+\Sigma} - 10^{\beta x+\Sigma}}{10^{\beta x+\Sigma}} = 10^{\beta v} - 1 \end{aligned} \quad (2)$$

where v was the input variation, x the initial input value and Σ represents the remaining, unchanged terms of Eqn (1). Although seed bank, weather and soil texture variables were included in the present analysis, their results (as well as the analysis of additional output variables) will only be presented in the Supplementary Material available online (Supplementary Material) to focus on cropping system components.

Identification and use biophysical indicators

To identify biophysical indicators for optimizing operation dates, the targeted operation date was removed from Eqn (1). The residuals of this new regression were then analysed successively as a function of biophysical indicators, i.e. the cumulated thermal time and the cumulated rainfall since harvest or sowing until the day of the operation, soil moisture and soil structure on the operation day, as well as weed density and stage on the operation day, with a linear regression:

$$\begin{aligned}&\text{Relative weed variation} \\ &= \text{residuals of Eqn (1)} \\ &= \text{constant} + ax + bx^2 + cx^2 \\ &\quad + d \log_{10}(x+1) + \text{error} \end{aligned} \quad (3)$$

where x was one of the biophysical indicators. x was introduced in different forms to allow the best representation of weed variation as a function of the indicators. Equation (3) was only applied to those data where the operation was implemented, e.g. only simulations with tillage were used to test indicators for tillage dates. To be acceptable and operational, indicators had to present the following characteristics: (1) the relationship linking relative weed density to the indicator was required to present a minimum value or decrease to a sill value for high indicator values; (2) the measurement of the indicators had to be feasible and (3) their optimization should not have any large detrimental secondary effect on other agronomic factors.

https://doi.org/10.1017/S0021859612000159 Published online by Cambridge University Press

Only the best indicators will be presented here; the detailed results can be found in the online appendix (Supplementary Material).

To optimize the choice of management tools, two different approaches were used. In the case of mechanical weeding, Eqn (3) was completed with a weeding tool effect as well as all interactions between the tool and the different x variables:

$$\begin{aligned}\text{Relative weed variation} &= \text{residuals of Eqn (1)}\\ &= \text{constant} + a_{\text{weeding tool}} \times x\\ &\quad + b_{\text{weeding tool}} \times x^2 + c_{\text{weeding tool}} \times x^3\\ &\quad + d_{\text{weeding tool}} \times \log_{10}(x+1) + e_{\text{weeding tool}} + \text{error}\end{aligned} \tag{4}$$

In the case of ploughing *v*. no ploughing, the method was more complicated. To calculate the residuals, Eqn (1) (minus the ploughing variables) was modified by replacing the initial seed bank variables by the crops and the management techniques of the five previous years (Colbach *et al.*, 2012; Supplementary Material). Residuals were then analysed as a function of the weed infestation (i.e. mature weeds at crop harvest) in the previous crop:

$$\begin{aligned}\text{Relative weed variation}_N &= \text{constant}\\ &\quad + a_{\text{ploughing}} \times \log_{10}(\text{weed density}_{N-1} + 1)\\ &\quad + c_{\text{ploughing}} + \text{error}\end{aligned} \tag{5}$$

Then as a function of the ratio of weed densities in the previous *v*. pre-previous crop:

$$\begin{aligned}\text{Relative weed variation}_N &= \text{constant}\\ &\quad + a_{\text{ploughing}} \times \frac{\text{weed density}_{N-1} + 1}{\text{weed density}_{N-2} + 1}\\ &\quad + b_{\text{ploughing}} \times \log_{10}\left(\frac{\text{weed density}_{N-1} + 1}{\text{weed density}_{N-2} + 1}\right)\\ &\quad + c_{\text{ploughing}} + \text{error}\end{aligned} \tag{6}$$

The same approach was used for comparing superficial *v*. deep ploughing (at least 0·19 m deep) and low *v*. high-frequency tillage (two or more tillage operations).

RESULTS

Simulated weed infestation

Both weed seed and plant densities varied considerably among simulations, from values close to zero to several thousand seedlings up to *c*. 10 000 seeds (Fig. 1). Distributions were highly skewed towards smaller values, particularly for plant densities and seed

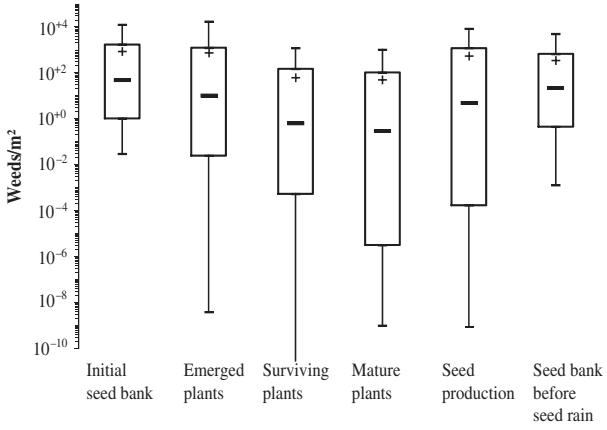


Fig. 1. Weed seed and plant densities at different stages throughout the annual simulation. Box-and-whisker plots show 1, 10, 50, 90 and 99% percentiles, + shows mean values.

production. Mean seed bank density at the onset of the last simulated year was 6311, resulting in a mean emergence density of 755 seedlings of which only a mean proportion of 0·08 and 0·07 of seedling survived up to harvest and maturity, respectively. The latter produced a mean of 3872 seeds, which would increase seed bank by *c*. 60% after seed bank replenishment if there were no seed bank decrease. During the year analysed, the seed bank decreased by approximately the same value, resulting in an apparent demographic stability. Simulations, however, differed greatly: in 0·10 of the simulations, the seed bank after seed rain was divided by three in 1 year whereas in another 0·10, it was multiplied by more than 17.

Contribution of the various simulation factors

Plant densities mostly depended on initial seed bank characteristics, though the contribution of the latter decreased with the 'lateness' of the stage, i.e. the contribution was lower for mature than for emerged plants (Table 2). Seed production depended even less on initial seed bank. However, the magnitude of the final seed bank before the new seed rain depended almost entirely on seed bank characteristics. Soil characteristics were negligible, while weather only explained 0·02–0·08 of above-ground weed densities, with a slight increase from 'early' (i.e. emerged plants) to 'late' stages (i.e. seed production). Its impact on the final seed bank was small. The effect of crop management increased from 0·01 for the earliest to 0·20 for the latest post-emergence stage; it was negligible for final seed bank. The effect of the width of the different agricultural tool was never significant.

https://doi.org/10.1017/S0021859612000159 Published online by Cambridge University Press

https://doi.org/10.1017/S0021859612000159 Published online by Cambridge University Press

Table 1. *Significant management techniques identified by Eqn (1) and subsequent relative variations (%) in weed infestation in winter wheat*

Tillage variables	Simulated range*	Tested variation in input variable	Resulting variation in weed infestation (%)§				Explanation
			Total density	Mature plants	Seed production	Seed bank	
a. Tillage‡							
Number of operations							
Total (if no ploughing)	[0, 7]	+1 operation	−9	−5	−18	−5	Stimulates fatal summer germination (see also Fig. 6)
Before ploughing	[0, 6]	+1 operation	NS**	NS	NS	−5	Stimulates fatal germination in fresh seeds
After ploughing	[0, 6]	+1 operation	−4	NS	−14	−5	Stimulates fatal germination in excavated seeds
Rolling	[0, 6]	+1 operation	NS	NS	+17	NS	Buries seeds slightly without stimulating germination; if too early, reduces fatal summer germination in fresh seeds
Ploughing	{yes, no}	Yes *v.* no	−37	−33	−67	+90	Buries seeds too deeply for germination and emergence
Date	[previous harvest, last tillage]	1 month delay	NS	NS	NS	−4	Leaves more time for fresh seeds on soil surface to germinate before burial
Depth (m)	[0·15, 0·30]	+0·05 m	NS	NS	+15	−10	Excavates more seeds and stimulates their germination
Skim-coulter width (m)	0 or [0·03, 2/3depth]	+0·04 m	−3	−4	−6	NS	Buries more fresh seeds too deeply for germination and emergence
Post-ploughing tillage							
Date	[ploughing, last tillage]	1 month delay	NS	NS	NS	NS	Leaves more time for seeds excavated by ploughing to germinate
Depth (m)	= *f* (tool)	+0·02 m	NS	NS	NS	+2	Buries more seeds excavated by ploughing and inhibits their germination
Tool	All except plough†	Chisel	+11	NS	NS	−29	Rolling buries seeds slightly without stimulating their germination, thus improving their survival. The more tools decrease seed bank and increase emergence, the lower their burial rates of superficial seeds and the higher their excavation rate of deep seeds. A rotavator also fragments deeper layers, thus facilitating deep emergence which is late and unproductive and even decreased seed production on earlier, productive seedlings
		Power harrow	NS	NS	NS	−4	
		Rotavator	NS	NS	−24	NS	
		0·10 m deep	NS	NS	NS	−4	
		Cover crop	−11	−12	−21	NS	
		Roll	NS	NS	NS	+9	
		Other tools	NS	NS	NS	NS	
First tillage after harvest							
Date	[previous harvest, last tillage]	1 month delay	+5	+7	+9	NS	Delays stimulation of fatal summer germination
Depth (m)	= *f* (tool)	+0·02 m	NS	−1	NS	+2	Buries more seeds too deeply for germination (see also choice of tools)
Tool	All†	Chisel	NS	NS	NS	−15	Tools were little differentiated but their ranking was compatible with that observed for post-ploughing. The additional tool here, mouldboard plough, confirms the processes listed above, showing that seed burial increases seed production because of reduced fatal summer germination
		Rotavator	NS	NS	NS	+8	
		Roll	NS	NS	NS	+21	
		Mouldboard plough	NS	NS	+16	NS	
		Other tools	NS	NS	NS	NS	
Last tillage							
Date	[sowing date −7, sowing date]	1 month delay	−49	−50	−56	−3	Delays sowing and thus leaves more time for fatal germination before crop sowing
Speed (km/h)	[4, 12]	+2 km/h	NS	−2	NS	NS	Uproots more seedlings

https://doi.org/10.1017/S0021859612000159 Published online by Cambridge University Press

Depth (m)	= *f* (tool)	+0·02 m	−5	−7	−10	NS	Buries more seeds too deeply for germination and emergence
Tool	See next column	Power harrow	−8	NS	NS	NS	The deeper the tool tills, the less germination and emergence
		Uniform 0·05 m deep	NS	NS	NS	+3	
		Uniform 0·10 m deep	−27	−20	−33	+5	
		Harrow	NS	NS	NS	+5	
Aggregated tillage variables							
Mean time between operations (days)		+10 days	NS	NS	NS	+1	Less time for frequent operations and fatal summer germination
Mean depth (m)		+0·05 m	+13	+17	NS	−12	Stimulates more germination and emergence

			Resulting variation in weed infestation (%)§				
Sowing variables	Simulated range*	Tested variation in input variable	Total density	Mature plants	Seed production	Seed bank	Explanation
b. Crop sowing††							
Date of last tillage (if any)	[sowing date − 7, sowing date]	1 month delay	−49	−50	−56	−3	Delays sowing and thus leaves more time for fatal germination before crop sowing
Sowing date (if no tillage)	[1 Sep, 30 Nov]	1 month delay	−5	−7	−29	NS	Leaves more time for fatal germination before crop sowing
Sowing date (if tillage)	[1 Sep, 30 Nov]	7 days delay	+16	+16	+15	NS	The later sowing date relative to the last tillage date, the more time weed seedlings have time to establish before crop emergence
Sowing density (seeds/m^2)	[100, 500]	+50 seeds/m^2	−5	−5	−6	NS	More competition for the weed

			Resulting variation in weed infestation (%)§				
Herbicide variables	Simulated variation*	Tested variation in input variable	Total density	Mature plants	Seed production	Seed bank before seed rain	Explanation
c. Herbicides#							
Number of operations							
Before sowing if tillage	{yes, no}	Yes *v*. no	−16	−7	−67	NS	Cleans field before sowing, slightly more important if no tillage
Before sowing if no tillage	{yes, no}	Yes *v*. no	−16	−7	−68	NS	
After sowing	[0, 4]	+1 operation	−21	−21	−39	NS	Kills more seedlings in crop
Herbicide before sowing							
Date	[sowing date − 30, sowing date]	1 month delay	NS	NS	+11	NS	
Number of tillage operations after herbicide	[0,7]	+1 operation	+7	NS	NS	NS	Stimulates germination of new seedlings after spraying
First herbicide after sowing							
Date	[sowing date, harvest date]	1 month delay	−2	−1	−4	NS	Less seedling emergence after spraying
Efficiency	[0, 1]	+0·20	NS	+3	NS	NS	For a given total efficiency over cropping season, better to concentrate highest efficiency on last than on first herbicide

https://doi.org/10.1017/S0021859612000159 Published online by Cambridge University Press

Table 1. (*Cont.*)

Herbicide variables	Simulated variation*	Tested variation in input variable	Resulting variation in weed infestation (%)§ Total density	Mature plants	Seed production	Seed bank before seed rain	Explanation
Penetration mode	See next column	Via root	−5	−9	−10	NS	Also kills seeds that have germinated but not yet emerged
		Via leaf	+5	+9	+4	NS	Does not kill seedlings that have not yet emerged
		Via both	0	0	+5	NS	
Last herbicide after sowing							
Date	[sowing date, harvest date]	1 month delay	NS	−2	+4	NS	Can be too late to avoid seed production though it kills more late-emerging plants
Aggregated variables							
Mean efficiency	[0, 1]	+0·20	−20	−23	−35	NS	Kills more seedlings

Weeding variables	Simulated variation*	Tested variation in input variable	Resulting variation in weed infestation (%)§ Total density	Mature plants	Seed production	Seed bank before seed rain	Explanation
d. Mechanical weeding&							
Number of operations	[0, 2], [0,6] if no herbicides	+1 operation	−5	NS	−18	−3	Kills more seedlings, stimulates more germination
First weeding							
Date	[sowing date, harvest date]	15 days later	NS	NS	−4	−1	Less seedling emergence after operation, stimulates more germination
Tool	See next column	Harrow	+16	+53	+1250	0	Rotary hoe tills both inter-row and crop row and uproots large plants, harrow only uproots small plants, hoe only works inter-row and does not uproot seedlings that have not yet emerged
		Hoe	+2	+84	+612	−2	
		Rotary hoe	−18	−137	−1863	+1	
Last weeding							
Date	[sowing date, harvest date]	15 days later	−2	−6	−7	NS	Less seedling emergence after operation
Depth (m)	[0·01,0·03], [0·01,0·05] for hoe	+0·01 m	+10	NS	NS	NS	Stimulates more germination
Tool	See next column	Harrow	+51	+60	+138	NS	Rotary hoe tills both inter-row and crop row and uproots large plants, harrow only uproots small plants, hoe only works inter-row and does not uproot seedlings that have not yet emerged
		Rotary hoe	+12	NS	NS	NS	
		Hoe	NS	NS	NS	NS	

https://doi.org/10.1017/S0021859612000159 Published online by Cambridge University Press

Management variables	Simulated variation*	Tested variation in input variable	Resulting variation in weed infestation (%)§ Total density	Mature plants	Seed production	Seed bank before seed rain	Explanation
Aggregated variables							
Mean depth (m)	[0·01,0·05]	+0·01 m	NS	+4	+13	NS	Stimulates more germination
Mean weeded area	[0,1]	+0·10	−8	−10	−20	NS	Kills more seedlings
Mean speed (km/h)	[4, 8]	+2 km/h	NS	−5	−7	NS	Uproots more seedlings
Time between operations		+15 days	NS	NS	+5	NS	Can be too late to destroy large seedlings and/or avoid seed production
e. Other variables$							
Nitrogen fertilizer (total kg N/ha)	[20, 400]	+30 kg N/ha	NS	NS	+3	NS	Improves flower production per head
Weed seed amount spread via manure	[1, 50 000]	+1000 seeds/m^2	NS	NS	+1	NS	Adds non-dormant seeds in summer
Harvest date	[1 Jun, 1 Aug]	15 days delay	NS	+7	+76	−2	Leaves more time for germination, emergence and seed production in crop

* Probabilities for choosing options were not uniform (Supplementary Material).
† {mouldboard plough, covercrop, chisel, roll, rotavator, spring tine, power harrow, uniform 5-cm-deep, uniform 10-cm-deep, harrow}.
‡ Variables not significant at $P \leqslant 0{\cdot}05$ were ploughing speed, inversion, ratio, skim-coulter depth, post-ploughing speed and mean tillage speed.
§ For significant variables, relative variations are calculated from regression parameters δ_i as $10^{\delta \cdot v} - 1$, where v is the tested factor variation.
** NS, not significant at $P \leqslant 0{\cdot}05$.
†† Last tillage is carried out at sowing or during the week preceding sowing.
# Variables not significant at $P \leqslant 0{\cdot}05$ were efficiency and penetration mode of pre-sowing and last post-sowing herbicides as well as mean time between successive operations.
& Variables not significant at $P \leqslant 0{\cdot}05$ were tractor speed, tilling depth and weeded area of first mechanical weeding as well as speed and weeded area of last weeding.
$ Variables not significant at $P \leqslant 0{\cdot}05$ were manure type, nitrogen amount spread via manure as well as number of tillage operations after manure spreading.

Table 2. *Variability in simulated weed output variables in winter wheat explained by* AlomySys *input variables. Partial and total* R^2 *of Eqn (1)*

	Simulated output variables (weeds/m^2)				
AlomySys input variables	Plants emerging before and during the crop	Surviving plants at harvest	Mature plants at harvest	Seed production	Seed bank before seed rain
Seed bank	0·79	0·58	0·46	0·42	0·96
Soil characteristics	0·00	0·00	0·01	0·01	0·00
Weather series	0·03	0·02	0·04	0·08	0·00
Tool width	0·00	0·00	0·00	0·00	0·00
Crop management	0·01	0·11	0·14	0·20	0·01
Unexplained variability	0·16	0·29	0·36	0·30	0·03
Total R^2	0·84	0·71	0·64	0·70	0·97

Table 3. *Variability in simulated weed output variables explained by crop management variables. Proportion of partial* R^2 *of Eqn (1) due to crop management*

	Simulated output variables (weeds/m^2)				
AlomySys input variables	Plants emerging before and during the crop	Surviving plants at harvest	Mature plants at harvest	Seed production	Seed bank before seed rain
Tillage	0·72	0·13	0·11	0·09	0·89
Sowing date	0·09	0·02	0·02	0·04	0·00
Sowing density	0·00	0·07	0·06	0·02	0·00
Herbicide	0·01	0·66	0·41	0·30	0·00
Mechanical weeding	0·14	0·12	0·37	0·15	0·07
Nitrogen	0·00	0·00	0·00	0·01	0·00
Manure	0·04	0·00	0·00	0·01	0·00
Harvest date	0·00	0·00	0·03	0·39	0·04

Among the crop management variables, tillage and, to a lesser degree, mechanical weeding were most important for determining the total emergence density (Table 3). These are the techniques that mostly determine seed germination via seed burial, dormancy breaking and the stimulation of germination flushes; they also influence emergence via their effect of pre-emergent seedling mortality due to seed depth and soil compaction. Sowing date was important because it determined the position of the weed seed dormancy cycle relative to the crop cycle. Manure had a slight effect through adding non-dormant seeds to the soil, thus boosting additional germination. Nitrogen fertilizer did not have any effect on emergence timing because it did not affect the soil seed bank processes, only the number and dormancy of the next weed seed rain. Sowing density and harvest did not influence emergence because they did not influence pre-emergent processes. Herbicides had a very slight effect because root-entering herbicides could kill seedlings that had yet to emerge.

When looking at surviving and mature plants at harvest and their seed production, techniques affecting post-emergence survival became much more significant, with herbicides and, again, mechanical weeding now the dominant techniques (Table 3). Seed density also became important, because of crop-weed competition. Harvest date was the most important management technique for determining the variability in weed seed production because it determined the time left to weed plants to mature before their destruction by the harvest equipment.

The situation was very different for the seed bank found at crop harvest, prior to the addition of the newly produced seeds. This seed bank almost entirely depended on tillage and, to a small degree, on mechanical weeding, via their effect of seed burial, dormancy breaking and germination stimulation. The

https://doi.org/10.1017/S0021859612000159 Published online by Cambridge University Press

Table 4. *Summary of advice for controlling autumnal grass weeds in winter wheat*

Management strategies	Option	Optimal choices and condition
Tillage	All	As many operations as possible, particularly if infestation of previous crop >0·7 times that of pre-previous crop
	Shallow tillage	In moist conditions, after at least 50 mm of rainfall since harvest
	Plough?	If infestation of previous crop >20 weeds/m^2 and particularly, if previous infestation >0·3 times pre-previous infestation. Plough at 100–200 mm of rainfall since previous harvest
	Plough deeper than 0·20 m?	If infestation of previous crop >3–4 weeds/m^2 and particularly, if previous infestation >0·7 times pre-previous infestation
	Shallow tillage	In moist conditions, with tools limiting seed burial. Till at 75–125 mm rainfall since ploughing
	Last tillage	At crop sowing, in dry conditions, as deep as possible and burying as much as possible
Sowing	Date	With last tillage As late as possible in autumn, delay at least until 175 mm rainfall since harvest
	Density	As high as possible
Herbicide	Pre-sowing	After the last tillage but one, if the last tillage is not expected to 'clean' the field
	Post-sowing	As many operations as possible, with the highest possible efficiency, particularly for the last application. Optimum spraying date is 200 °C days after sowing. Prefer root-penetrating herbicides for first application
Mechanical weeding		As many operations as possible, minimizing tilling depth, maximizing the tilled area and tractor speed. At weed densities <1 weed/m^2, prefer harrow to hoe and, particularly, to rotary hoe. At densities >80 (first) or 40 plants/m^2 (last weeding), prefer rotary hoe
Nitrogen		Avoid over-fertilization
Manure		Compost manure to reduce viable seed content
Harvest		Do not delay

only other relevant technique was the date of the crop harvest, timing the moment at which the surviving seed bank was calculated.

The effect of crop management variables

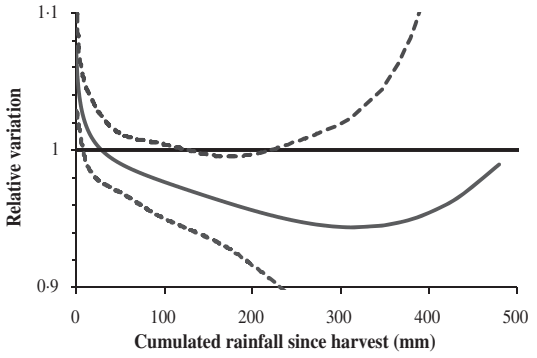
The crop management variables that presented a significant effect on at least one of the weed variables are listed in Table 1, together with a quantitative estimation of this effect as well as its probable cause. Variations were similar for plants and seed production in crops though effects were usually most frequent and variations largest for seed production. The variations in surviving seed bank (prior to the new seed rain) were usually opposite to those in plants, pointing to germination as a major process, emptying the former and resulting in the increase in the latter after subsequent pre-emergent growth. Only a few changes in management techniques (e.g. increasing the number of tillage operations) decreased both weed plants and surviving seed bank. These were due to an increase in fatal summer germination, i.e. in the germination of seeds that did not emerge or resulted in seedlings that were killed before crop sowing. The effect of some characteristics was stable, for instance the number of herbicide sprayings, whether applied before or after crop sowing, always decreased weed infestation. For other techniques, the effect depended on the date of the operation, for instance tools which provided deep tillage and/or burying of weeds should be avoided for early tillage because they reduce fatal summer germination whereas they would be best for the last tillage prior to or at the time of crop sowing, because they bury weeds too deeply for them to germinate and emerge during the crop.

Identifying biophysical indicators for decision-making

Optimizing the choice of tools and dates as a function of biophysical indicators

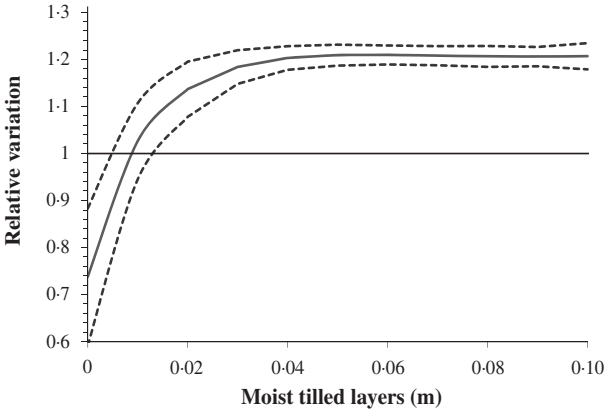
Ploughing date could best be optimized by taking into account the cumulated rainfall since previous harvest (Fig. 2). Relative weed seed production steadily

https://doi.org/10.1017/S0021859612000159 Published online by Cambridge University Press



$y = 0{\cdot}0754 + 0{\cdot}000246x - 1{\cdot}71\times10^{-6}x^2 + 3{\cdot}0\times10^{-9}x^3 - 0{\cdot}0551\log_{10}(x+1)$
$R^2 = 0{\cdot}0019$

Fig. 2. Indicator for optimizing mouldboard ploughing date. Relative weed seed production in winter wheat as a function of cumulated rainfall from previous harvest to ploughing day (continuous line = regression, dashed lines = 95% confidence interval). Results of Eqn (3).



$y = -0{\cdot}462 - 19{\cdot}5x + 101x^2 - 221x^3 + 1{\cdot}57\log_{10}(100x+1)$ $R^2 = 0{\cdot}0031$

Fig. 3. Variation of weed seed production as a function of soil moisture before the last tillage preceding winter wheat (continuous line = regression with, dashed lines = 95% confidence interval).

decreased when ploughing was delayed until 200 mm of cumulated rainfall after previous harvest, because this left more time for fatal summer germination before burial, particularly from fresh seeds. After that date, the effect became variable, with an increasing risk of weed infestation because seeds excavated and stimulated by ploughing and subsequent tillage presented a higher probably of emerging after crop sowing. The dates of first, post-ploughing and last tillage operations could also be optimized with cumulated rainfall (Supplementary Material) for details and synthesis in Table 4). Delaying the first tillage after optimum timing of 50 mm did not increase weed density.

The rainfall indicator was better than the number of days or thermal time since harvest because it also integrated the seed requirement for soaking to germinate and that rainfall also contributes to breaking dormancy in fresh seeds. Relative weed seed production was also negatively correlated with the number of tilled moist layers (i.e. with a water potential above the base value for germination) for all but the last tillage. These relationships cannot be used directly for decision-making because soil water potential is too difficult to measure. However, this indicator revealed that the last tillage should be carried out in conditions as dry as possible because weed risk increased steadily with soil moisture (Fig. 3), which favoured germinating seeds emerging in the crop.

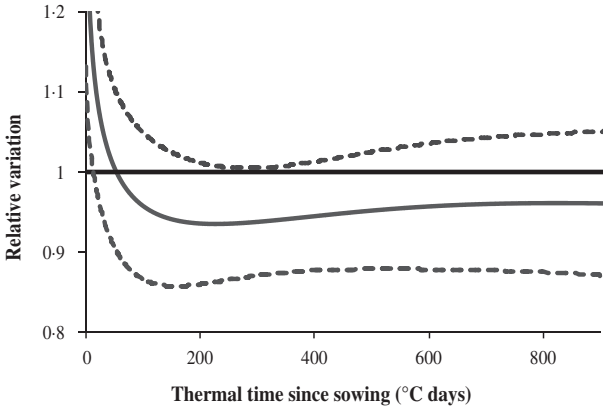
None of the tested indicators was able to optimize sowing date. The timing of herbicide spraying was best optimized with thermal time, though a similar but less significant relationship could be obtained for cumulated rainfall (Supplementary Material). Spraying was best delayed until 200 °C days after sowing (Fig. 4) to leave more time for seedlings to emerge and be killed by the herbicide. After 300 °C days, the weeds were too large and numerous to be destroyed. There was no significant difference between herbicides with different penetration modes.

In the case of mechanical weeding, both tools and timing could be optimized. Weed density was the indicator with the highest explanatory power (i.e. highest R^2) though thermal time and cumulated weed foliar stage could also be used (Supplementary Material). When weed densities were low (< 1 plant/m^2 approximately), the optimal tools for both first and last weeding were hoeing and, to a lesser degree, harrowing; at that time, plants were still small and the proportion of seedlings yet to emerge was high, which were the stages best uprooted by these tools (Fig. 5). At greater densities, a rotary hoe was the optimal tool because it also uprooted large weeds, but its use was most effective at weed densities below 80 and 40 plants/m^2 for the first and last operations, respectively.

Optimizing tillage choices as a function of past weed infestations

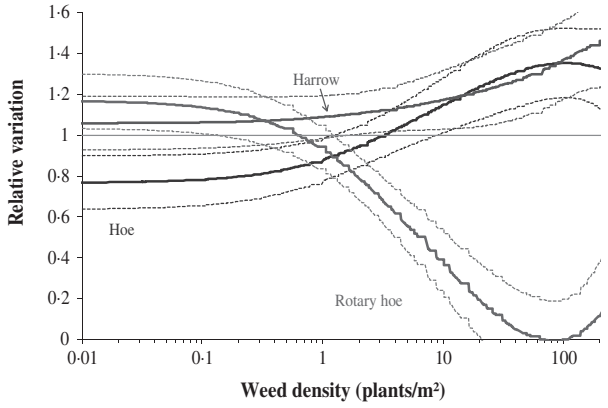
Although ploughing was identified as the usual optimal choice over no-ploughing (Table 1*a*), analyses taking account of past weed infestation showed that this was only true when the weed infestation in the previous crop exceeded *c*. 20 plants/m^2 (Supplementary Material). Moreover, ploughing was only the best option when the infestation of the

https://doi.org/10.1017/S0021859612000159 Published online by Cambridge University Press



$y = 0{\cdot}436 + 0{\cdot}000776x - 6.18 \times 10^{-7} x^2 + 2{\cdot}00 \times 10^{-11} x^3 - 0{\cdot}275 \log_{10}(x+1)$
$R^2 = 0.0175$

Fig. 4. Indicator for optimizing the timing of the first herbicide after crop sowing. Relative weed seed production in winter wheat as a function of thermal time (base 0 °C) from crop sowing to operation day (continuous line = regression with, dashed lines = 95% confidence interval). Results of Eqn (3).



Harrow: $y = -0{\cdot}232 - 0{\cdot}00210x - 1{\cdot}71 \times 10^{-6} x^2 - 8.00 \times 10^{-10} x^3 + 0{\cdot}385 \log_{10}(x+1)$
Hoe: $y = 0{\cdot}170 + 0{\cdot}00148x - 3{\cdot}12 \times 10^{-6} x^2 + 1{\cdot}10 \times 10^{-9} x^3 + 0{\cdot}0963 \log_{10}(x+1)$
Rotary hoe: $y = 0{\cdot}169 + 0{\cdot}00535x - 6{\cdot}19 \times 10^{-6} x^2 + 2{\cdot}10 \times 10^{-9} x^3 - 0{\cdot}819 \log_{10}(x+1)$
$R^2 = 0{\cdot}153$

Fig. 5. Indicator for optimizing the date and tool of the first mechanical weeding operation. Relative weed seed production in winter wheat as a function of weed density on the operation day (continuous line = regression with, dashed lines = 95% confidence interval). Results of Eqn (4).

previous crop exceeded *c*. 0·3 times that of the pre-previous crop (Fig. 6).

The situation was even more complicated for ploughing depth. The initial analysis showed weed infestation to increase with ploughing depth (Table 1*a*). The analysis as a function of weed density in the previous crop showed this to be true only when

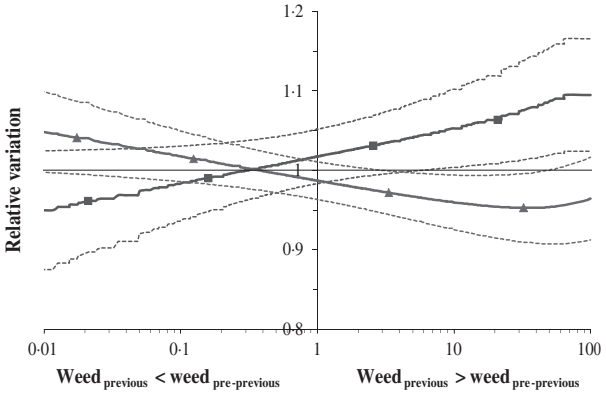


Fig. 6. Variation of weed seed production in ploughed (▲) and un-ploughed (■) winter wheat as a function of the ratio of the weed densities in the previous *v*. pre-previous crop (continuous line = regression with, dashed lines = 95% confidence interval). Results of Eqn (6), $R^2 = 0{\cdot}011$.

this density was lower than *c*. 3–4 plants/m^2 (Supplementary Material). In addition, deep ploughing was best when weeds in the previous crop exceeded *c*. 0·7 times those in the pre-previous crop (Fig. 7). Similarly, high-frequency tillage (two or more operations) was shown to be most interesting when the previous weed infestation exceeded *c*. 0·4 times the pre-previous infestation (Supplementary Material).

DISCUSSION

Implications for designing grass weed management strategies

The first major result of the present study was the quantitative, synthetic ranking of the crop management effects in the short-term, identifying the optimal choices for each management technique (Table 4). These are particularly interesting for techniques with contradicting effects, strong interactions with the environment, and many possible choices such as tillage. Other conclusions are less original, e.g. crop sowing density, but confirm reports from field trials and surveys (e.g. Chauvel *et al*. 2001). But even for *a priori* evident advice such as 'maximize herbicide efficiency', new indications could be identified, such as the focus on the last spraying rather than the first. Similar advice on grass weed management has already been compiled in previous reports (e.g. Moss & Clarke 1994), but the present management rules are much more detailed (e.g. distinction of different tillage types), quantify effects (e.g. maximize efficiency of the last rather than earlier herbicide sprayings) and adapt the

https://doi.org/10.1017/S0021859612000159 Published online by Cambridge University Press

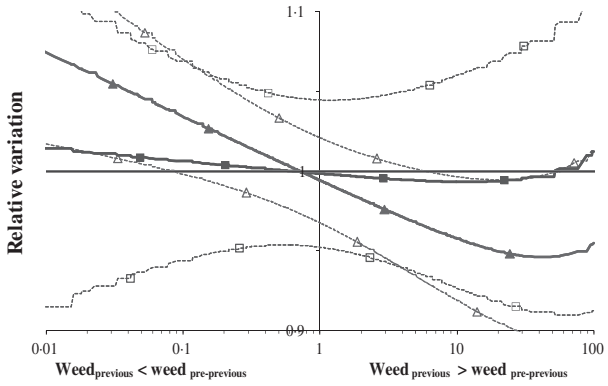


Fig. 7. Variation of weed seed production in deeply (deeper than 0·19 m: ▲, △) and superficially ploughed (less than 0·19 m: ■, □) winter wheat as a function of the ratio of the weed densities in the previous *v*. pre-previous crop (continuous line = regression with, dashed lines = 95% confidence interval). Results of Eqn (6), $R^2 = 0{\cdot}011$.

rules to weed (e.g. density prior to operation) and environmental conditions (e.g. rainfall).

However, the present advice is conditional to the model quality, although many aspects of the model have been satisfactorily evaluated, e.g. tillage and sowing date (Colbach *et al*. 2006*a*, 2007). Moreover, most of the major effects identified in the present paper are consistent with previous field observations and should therefore be robust in a large range of field conditions, e.g. the decrease in blackgrass or similar species in case of mouldboard ploughing or delayed sowing (Schneider *et al*. 1984; Chauvel *et al*. 2001; Moss *et al*. 2007; Cirujeda & Taberner 2009). Literature reports on minor factors such as nitrogen fertilizer effects are partial and inconsistent (e.g. blackgrass biomass decrease in pot-grown weed-wheat mixtures: Naylor (1972*b*); blackgrass seed production increase in cereal crops: Chauvel 1996; Chauvel *et al*. 1996) and make it difficult to check the robustness of the present results. Similarly, the advice on optimal tools for mechanical weeding is only valid if a rotary hoe does indeed fail to destroy seedlings that have not yet emerged, as assumed by ALOMYSYS. Further tests, of the model itself and of the present advice, are therefore necessary.

Though the present methodology has already been used with other weed dynamics models (Colbach *et al*. 2004; Tricault *et al*. 2009), the present study could improve the initial approach with the integration of biophysical indicators for optimizing management strategies (e.g. delay the first tillage until 50 mm rainfall after harvest). This original approach contributes to improving understanding of the variability in the crop management effects and to making management advice much more robust, optimizing it for different biophysical conditions. Moreover, these flexible rules are much closer to the actual farming decision processes (Aubry *et al*. 1998). Indeed, operations are usually not executed at a fixed date, irrespective of conditions, but depend on diverse factors such as weather, soil moisture, crop and weed growth stages, trafficability restrictions, competition with other farm work etc. (Macé *et al*. 2007).

The present study demonstrated the enormous importance of interactions, not only among crop management techniques but also between techniques and biophysical conditions in the field. The latter have been partially integrated into the present, innovative approach, representing the variability in management effects on weed infestation as a function of different biophysical indicators. However, a large proportion of variability remained unexplained, even when integrating these indicators. It is possible that a part of this variability is not actually pertinent and an artefact of the present simulation plan, where all management variables were randomized. Many combinations were probably highly improbable in farming reality. Consequently, more focused simulation studies are necessary, starting with existing or probable cropping systems and testing prospective scenarios based on the present guidelines and biophysical indicators. Such an approach has already been attempted with fixed-date scenarios (Colbach *et al*. 2009, 2010*c*, *in press*; Mézière *et al*. 2011) but to the best of our knowledge, not yet with biophysical indicators.

Methodology

Though the present study developed an original addition to existing sensitivity analysis methods with the integration of biophysical indicators, it presents several major disadvantages. Firstly, the effect of crop management was only studied in a single crop, albeit the one where the studied weed species is most frequent and harmful (Van Himme & Bulcke 1975). Moreover, variable effects were represented as linear, with either a positive or negative effect. Actually, as the indicator analysis showed, effects are often more complex, e.g. weed infestation first decreased when tillage was delayed after harvest and later increased the closer to crop sowing the operation was executed. Lastly, the effect was only studied in the short-term, over 1 year. This is a considerable short-coming

https://doi.org/10.1017/S0021859612000159 Published online by Cambridge University Press

because weed seeds survive for several years, even short-lived grass species such as blackgrass (Lonchamp *et al*. 1984). The 1-year step thus neglected one of the major, known effects on weed dynamics, i.e. crop succession and the long-term effects of crop management (Chauvel *et al*. 2001; Bohan *et al*. 2011). This is, for instance, the case of seed burial by tillage (e.g. Naylor 1972*a*) partially seen here via increases in seed bank survival, of seed addition by manure (Pleasant & Schlather 1994; Miyazawa *et al*. 2004), of the primary dormancy of newly produced seeds due to modifications in emergence and maturity dates as well as nitrogen fertilization (Colbach & Dürr 2003; Swain *et al*. 2006).

The 1-year scale of the present analysis was a deliberate decision, to focus on interactions with biophysical field state variables. Long-term effects and interactions were studied in a companion paper, confirming most of the crop management effects observed in the present paper (Colbach *et al*. 2012).

CONCLUSION

The main new outcomes from the present study were the development of detailed and quantitative management rules for weed management adapted to weed (e.g. weed density prior to weeding) and environmental conditions (e.g. rainfall), leading to the identification of biophysical indicators pertinent for optimizing management decisions. From a methodology perspective, the present study adapted an existing method of sensitivity analysis for complex, multi-variate cropping system models to not only rank and quantify crop management effects, but also appreciate their variability as a function of biophysical field state variables.

To progress in the development of integrated weed management, additional simulation studies are necessary to study management effects and interactions in more contrasting and representative cropping system types, focusing on the trade-off between different techniques. For instance, how many more time-consuming (e.g. tillage) or yield-decreasing modifications (e.g. delayed sowing date) are necessary to compensate the elimination of a given herbicide application. Or, from a different perspective, how many herbicide applications become superfluous in a diversified rotation with frequent mouldboard ploughing. The latter question will necessitate additional preliminary sensitivity analyses which are presented in a companion paper (Colbach *et al*. 2012).

The present study considers only a single weed species, albeit a frequent and harmful one. The results could be tentatively extrapolated to species with similar traits (e.g. *Lolium*) but this would only be possible for a small number of species. Though the present authors have already carried out a similar sensitivity analysis with a very different weed (i.e. the spring-emerging broad-leaved crop relative, *Beta vulgaris* spp. *vulgaris*, Tricault *et al*. 2009), truly multi-specific weed dynamics models (Colbach *et al*. 2010*a*; Gardarin *et al*. *in press*) will be necessary to design integrated cropping systems.

SUPPLEMENTARY MATERIAL REFERENCE

Supplementary Material. Additional information and results for the paper 'Using a sensitivity analysis of a weed dynamics model to develop sustainable cropping systems. I. Annual interactions between crop management techniques and biophysical field state variables'. *Journal of Agricultural Science, Cambridge* 2012; Supplementary Material (available at http://journals.cambridge.org/AGS).

The present work was financed by INRA and ANR SYSTERRA ADVHERB (ANR-08-STRA-02).

REFERENCES

Aubertot, J. N., Lescourret, F., Bonato, O., Colbach, N., Debaeke, P., Doré, T., Fargues, J., Lô-Pelzer, E., Loyce, C. & Sauphanor, B. (in press). How to improve pest management in cropping systems. Effects of cultural practices on pest development. A review. *Agronomy for Sustainable Development*, *in press*.

Aubry, C., Papy, F. & Capillon, A. (1998). Modelling decision-making processes for annual crop management. *Agricultural Systems* **56**, 45–65.

Bohan, D. A., Powers, S. J., Champion, G., Haughton, A. J., Hawes, C., Squire, G., Cussans, J. & Mertens, S. K. (2011). Modelling rotations: can crop sequences explain arable weed seedbank abundance? *Weed Research* **51**, 422–432.

Chauvel, B. (1996). Variabilité de la production de semences chez le vulpin (*Alopecurus myosuroides* Huds.) en fonction de la culture. In *Proceedings of the Xe Congrès International sur la Biologie des Mauvaises Herbes* (Ed. INRA), pp. 43–50. Dijon, France: INRA.

Chauvel, B., Angonin, C. & Colbach, N. (1996). Blackgrass (*Alopecurus myosuroides* Huds) development and seed production in wheat. In *Proceedings of the 4th ESA Congress* (Eds M. K. van Ittersum, G. E. G. T. Venner & T. H. van de Geijn), pp. 528–529. Veldhoven-Wageningen: European Society for Agronomy.

https://doi.org/10.1017/S0021859612000159 Published online by Cambridge University Press

Chauvel, B., Guillemin, J. P., Colbach, N. & Gasquez, J. (2001). Evaluation of cropping systems for management of herbicide-resistant populations of blackgrass (*Alopecurus myosuroides* Huds.). *Crop Protection* **20**, 127–137.

Cirujeda, A. & Taberner, A. (2009). Cultural control of herbicide-resistant *Lolium rigidum* Gaud. populations in winter cereal in Northeastern Spain. *Spanish Journal of Agricultural Research* **7**, 146–154.

Colbach, N. (2010). Modelling cropping system effects on crop pest dynamics: how to compromise between process analysis and decision aid. *Plant Science* **179**, 1–13.

Colbach, N. & Debaeke, P. (1998). Integrating crop management and crop rotation effects into models of weed population dynamics: a review. *Weed Science* **46**, 717–728.

Colbach, N. & Dürr, C. (2003). Effects of seed production and storage conditions on blackgrass (*Alopecurus myosuroides* Huds.) germination and shoot elongation with time. *Weed Science* **51**, 708–717.

Colbach, N., Dürr, C., Roger-Estrade, J. & Caneill, J. (2005). How to model the effects of farming practices on weed emergence. *Weed Research* **45**, 2–17.

Colbach, N., Busset, H., Yamada, O., Dürr, C. & Caneill, J. (2006*a*). ALOMYSYS: modelling black-grass (*Alopecurus myosuroides* Huds.) germination and emergence, in interaction with seed characteristics, tillage and soil climate. II. Evaluation. *European Journal of Agronomy* **24**, 113–128.

Colbach, N., Chauvel, B., Gauvrit, C. & Munier-Jolain, N. M. (2007). Construction and evaluation of ALOMYSYS, modelling the effects of cropping systems on the blackgrass life-cycle. From seedling to seed production. *Ecological Modelling* **201**, 283–300.

Colbach, N., Dürr, C., Roger-Estrade, J., Chauvel, B. & Caneill, J. (2006*b*). ALOMYSYS: modelling blackgrass (*Alopecurus myosuroides* Huds.) germination and emergence, in interaction with seed characteristics, tillage and soil climate. I. Construction. *European Journal of Agronomy* **24**, 95–112.

Colbach, N., Gardarin, A. & Munier-Jolain, N. M. (2010*a*). FLORSYS: a mechanistic model of cropping system effects on weed flora based on functional relationships with species traits. In *15th International EWRS Symposium Kaposvár, Hungary* (Eds L. Bastiaans, C. Bohren, S. Christensen, B. Gerowitt, P. Hatcher, H. Krähmer, P. Kudsk, B. Melander, E. Pannacci, B. Rubin, J. Streibig, F. Tei, A. Thompson, K. Torresen & M. Vurro), pp. 157–158. Budapest, Hungary: Asszisztencia Congress Bureau Ltd.

Colbach, N., Granger, S. & Mézière, D. (2012). Using a sensitivity analysis of a weed dynamics model to develop sustainable cropping systems. II. Long-term effect of past crops and management techniques on weed infestation. *Journal of Agricultural Science, Cambridge*. Published online doi:10.1017/S0021859612000160.

Colbach, N., Granger, S. & Munier-Jolain, N. M. (2009). Using weed dynamics models for evaluating and developing integrated cropping systems. In *XIIIème Colloque International sur la Biologie des Mauvaises Herbes, 8–10 September 2009, Dijon, France*, pp. 195–205. Dijon, France: INRA.

Colbach, N., Kurstjens, D. A. G., Munier-Jolain, N. M., Dalbiès, A. & Doré, T. (2010*b*). Assessing non-chemical weeding strategies through mechanistic modelling of blackgrass (*Alopecurus myosuroides* Huds.) dynamics. *European Journal of Agronomy* **32**, 205–218.

Colbach, N., Molinari, N. & Clermont-Dauphin, C. (2004). Sensitivity analyses for a model simulating demography and genotype evolutions with time. Application to GENESYS modelling gene flow between rape seed varieties and volunteers. *Ecological Modelling* **179**, 91–113.

Colbach, N., Schneider, A., Ballot, R. & Vivier, C. (2010*c*). Diversifying cereal-based rotations to improve weed control. Evaluation with the ALOMYSYS model quantifying the effect of cropping systems on a grass weed. *Oleagineux Corps Gras Lipides* **17**, 292–300.

Délye, C., Menchari, Y., Guillemin, J. P., Matéjicek, A., Michel, S., Camilleri, C. & Chauvel, B. (2007). Status of blackgrass (*Alopecurus myosuroides*) resistance to acetyl-coenzyme A carboxylase inhibitors in France. *Weed Research* **47**, 95–105.

European Union (2006). Regulation (EC) no 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC. *Official Journal of the European Union* L396 30.12.2006, 1–849.

Gardarin, A., Dürr, C. & Colbach, N. (in press). Modelling weed seed bank dynamics and emergence with species traits. *Ecological Modelling*.

Gressel, J. (2011). Global advances in weed management. *Journal of Agricultural Science, Cambridge* **149** (Suppl. 1), 47–53.

IFEN (2007). *Les Pesticides dans les Eaux – Données 2005*. Orléans: Institut Français de l'Environnement.

Kurstjens, D. A. G. & Perdok, U. D. (2000). The selective soil covering mechanism of weed harrows on sandy soil. *Soil and Tillage Research* **55**, 193–206.

Kurstjens, D. A. G., Perdok, U. D. & Goense, D. (2000). Selective uprooting by weed harrowing on sandy soils. *Weed Research* **40**, 431–447.

Lonchamp, J. P., Chadoeuf, R., Barralis, G. & Bourlier, M. (1984). Évolution de la capacité de germination des semences de mauvaises herbes enfouies dans le sol. *Agronomie* **4**, 671–682.

Macé, K., Morlon, P., Munier-Jolain, N. & Quéré, L. (2007). Time scales as a factor in decision-making by French farmers on weed management in annual crops. *Agricultural Systems* **93**, 115–142.

Mézière, D., Granger, S., Boissinot, F. & Colbach, N. (2011). Maîtriser les adventices graminées automnales sans herbicide: Quel est le Poids de l'histoire culturale? Evaluation avec un modèle de dynamique d'adventices. In *AFPP – Quatrième Conférence Internationale sur les Méthodes Alternatives en Protection des Cultures, Lille, France, 8–10 Mars 2011*, pp. 774–784. Paris, France: AFPP.

https://doi.org/10.1017/S0021859612000159 Published online by Cambridge University Press

Miyazawa, K., Tsuji, H., Yamagata, M., Nakano, H. & Nakamoto, T. (2004). Response of weed flora to combinations of reduced tillage, biocide application and fertilization practices in a 3-year crop rotation. *Weed Biology and Management* **4**, 24–34.

Moss, S. R. & Clarke, J. H. (1994). Guidelines for the prevention and control of herbicide-resistant black-grass (*Alopecurus myosuroides* Huds.). *Crop Protection* **13**, 230–234.

Moss, S. R., Perryman, S. A. M. & Tatnell, L. V. (2007). Managing herbicide-resistant blackgrass (*Alopecurus myosuroides*): theory and practice. *Weed Technology* **21**, 300–309.

Naylor, R. E. L. (1972*a*). Aspects of the population dynamics of the weed *Alopecurus myosuroides* Huds. in winter cereal crops. *Journal of Applied Ecology* **9**, 127–139.

Naylor, R. E. L. (1972*b*). The nature and consequence of interference by *Alopecurus myosuroides* Huds. on the growth of winter wheat. *Weed Research* **12**, 137–143.

Pleasant, J. M. & Schlather, K. J. (1994). Incidence of weed seed in cow (bos sp) manure and its importance as a weed source for cropland. *Weed Technology* **8**, 304–310.

Powles, S. B. & Yu, Q. (2010). Evolution in action: plants resistant to herbicides. In *Annual Review of Plant Biology*, Vol. 61 (Eds S. Merchant, W. R. Briggs & D. Ort), pp. 317–347. Palo Alto: Annual Reviews.

Rodenburg, J., Meinke, H. & Johnson, D. E. (2011). Challenges for weed management in African rice systems in a changing climate. *Journal of Agricultural Science, Cambridge* **149**, 427–435.

Rossing, W. A. H., Meynard, J. M. & van Ittersum, M. K. (1997). Model-based explorations to support development of sustainable farming systems: case studies from France and the Netherlands. *European Journal of Agronomy* **7**, 271–283.

Saltelli, A., Chan, K. & Scott, E. M. E. (2000). *Sensitivity Analysis*. Chichester, UK: John Wiley & Sons.

Schneider, W., Walter, H., Koch, W. & Kemmer, A. (1984). Möglichkeiten und Probleme der Integration ackerbaulicher Maßnahmen zur Unkrautbekämpfung im realen Betrieb – Beispiel aus dem Unterland, Baden-Württemberg. *Zeitschrift für Pflanzenkrankheiten und Pflanzenschutz, Sonderheft* **10**, 241–257.

Swain, A. J., Hughes, Z. S., Cook, S. K. & Moss, S. R. (2006). Quantifying the dormancy of *Alopecurus myosuroides* seeds produced by plants exposed to different soil moisture and temperature regimes. *Weed Research* **46**, 470–479.

Tricault, Y., Darmency, H. & Colbach, N. (2009). Identifying key components of weed beet management using sensitivity analyses of the GeneSys-Beet model in sugar beet. *Weed Research* **49**, 581–591.

Van Himme, M. & Bulcke, R. (1975). Distribution, extension et importance d'*Alopecurus myosuroides* Huds. en Europe. In *Proceedings of the European Weed Research Society Symposium on the Status, Biology and Control of Grassweeds in Europe*, pp. 23–54. Doorwerth, The Netherlands: European Weed Research Society.

https://doi.org/10.1017/S0021859612000159 Published online by Cambridge University Press