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Assessing non-chemical weeding strategies through mechanistic modelling of blackgrass (*Alopecurus myosuroides* Huds.) dynamics

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Abstract

Because of environmental and health safety issues, it is necessary to develop strategies that do not rely on herbicides to manage weeds. Introducing temporary grassland into annual crop rotations and mechanical weeding are the two main features that are frequently used in integrated and organic cropping systems for this purpose. To evaluate the contribution of these two factors in interaction with other cropping system components and environmental conditions, the present study updated an existing biophysical model (i.e. ALOMYSYS) that quantifies the effects of cropping system on weed dynamics. Based on previous experiments, new submodels were built to describe the effects on plant survival and growth reduction of mechanical weeding resulting from weed seedling uprooting and covering by soil, and those of grassland mowing resulting from tiller destruction. Additional modifications described the effect of the multi-year crop canopy of grassland on weed survival, growth, development and seed return to the soil. The improved model was used to evaluate the weed dynamics over 27 years in the conventional herbicide-based cropping system most frequently observed in farm surveys (i.e. oilseed rape/winter wheat/winter barley rotation with superficial tillage) and then

to test prospective non-chemical scenarios. Preliminary simulations tested a large range of mechanical weeding and mowing strategies, varying operation frequencies, dates and, in the case of mechanical weeding, characteristics (i.e. tool, working depth, tractor speed). For mechanical weeding soon after sowing, harrowing was better than hoeing for controlling weed seed production. The later the operation, the more efficient the hoeing and the less efficient the harrowing. Tractor speed had little influence. Increasing the tilling depth increased plant mortality but increased weed seed production because of additional seed germination triggering by the weeding tool. Decreasing the interrow width for hoeing was nefarious for weed control. The best combinations were triple hoeing in oilseed rape and sextuple harrowing in cereals. The best mowing strategy was mowing thrice, every 4-6 weeks, starting in mid-May. The best individual options were combined, simulated over 27 years and compared to the herbicide-based reference system. If herbicide applications were replaced solely by mechanical weeding, blackgrass infestation could not be satisfactorily controlled. If a three-year lucerne was introduced into the rotation, weed infestations were divided by ten. Replacing chisel by mouldboard ploughing before winter wheat reduced weed infestations at short, medium and long-term to a level comparable to the herbicide-based reference system.

Keywords. cropping system, weed dynamics, model, mechanical weeding, grassland, integrated crop protection

1. Introduction

Until a few years ago, weed management in Western Europe relied almost exclusively on herbicide applications. However, herbicide-resistant weeds are increasingly reported because of the repetitive use of similar active ingredients (Moss, 1987; Darmency and Gasquez, 1990; Gressel and Segel, 1990; Hole and Powles, 1997). In addition, herbicides are those pesticides that are most frequently identified in ground and surface water (IFEN, 2007). It therefore becomes necessary to develop other strategies for managing weeds. The situation is changing rapidly, with the extension of integrated pest management and organic agriculture. Consequently, there is an increasing amount of references for non-chemical weed management, both in organic and conventional farming. Syntheses have been published recently (Chicouene, 2007; Van Der Weide *et al.*, 2008) on mechanical weeding (i.e. tilling the soil during the cropping season to destroy weeds as opposed to tillage during summer fallow), on which non-chemical weed management often relies in annual crops. Multi-year crops such as temporary grassland or lucerne are already a frequent feature in organic rotations and are requested to increase in conventional rotations for ecological purposes. In these crops, mechanical weeding is mostly carried out during the first crop year, and weeds are mainly controlled with frequent mowing operations. For the latter, scientific knowledge is scarce.

It is now well recognized that models that quantify the effects of weed management techniques on weeds dynamics are valuable tools to design weed management strategies (Aubertot *et al.*, ; Rossing *et*

al., 1997). To understand and predict the variability in effects observed for given techniques and to use these models in a large range of conditions without reparametrising, mechanistic approaches where 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 conditions (*e.g.* soil structure) are necessary (Colbach and Debaeke, 1998; Colbach *et al.*, 2005). Though numerous demographic weed models have been developed in the past for cropping system effects (see reviews by Doyle, 1997; Colbach and Debaeke, 1998; Holst *et al.*, 2007), only a single available one answers to the previous requirements to date. The ALOMYSYS model (Colbach *et al.*, 2006a; 2006b; Colbach *et al.*, 2007) was developed for *Alopecurus myosuroides* Huds. (blackgrass), an annual grass-weed frequently found in autumn-sown crop rotations of Atlantic European countries (Van Himme and Bulcke, 1975) and increasingly tolerant to various herbicides (Moss, 1987; Gasquez, 1996). However, ALOMYSYS has not considered features such as mechanical weeding, mowing or multi-year crops. Consequently, the aim of the present paper was to integrate these techniques into ALOMYSYS. The structure of ALOMYSYS based on sub-models detailing the various life-cycle processes makes the addition of these techniques possible without modifying the core model. To evaluate the efficiency of the innovative techniques for managing weeds, a simulation methodology was proposed, combining farm surveys with simulations of individual techniques and comprehensive cropping systems, to identify efficient weed control strategies for farmers in a case study.

2. Material and methods

2.1. Model structure

2.1.1. The main features of ALOMYSYS

The structure of ALOMYSYS is described in detail by Colbach *et al.* (2006a; 2006b; 2007). Only the main aspects are described here.

The input variables of ALOMYSYS consist of:

- the above-ground climate: temperature and rainfall for each simulated day;
- the soil climate, either measured in the field or simulated with existing models such as STICS (Brisson *et al.*, 1998a): temperature, soil moisture and water potential for each day and for each of the 30 soil layers ranging from 0 to 30 cm;
- a description of the simulated location: soil texture and depth, initial soil structure (fragmented, intermediate, compacted) and initial soil moisture (dry, intermediate, moist)
- the initial seed bank: seed density and characteristics (age, weight, conditions of seed production) for each soil layer and the two seed age classes (freshly produced, older than one year);

- the cropping system during the whole simulated period, comprising the crop sequence including set-aside and cover crops, the date of all operations (tillage, sowing, herbicides, harvest) and their characteristics, *i.e.* tool, working depth etc. for tillage, active ingredient, rate and conditions (good, intermediate, bad) for herbicides, seed density for sowing, and total applied rate for nitrogen fertilization.

These input variables influence the annual life-cycle of blackgrass (Table 1), 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). All life-stages are described in output files, but the main output variables comprise daily emerging seedlings, total density of mature weeds at crop harvest, their seed production, and the seed bank consisting of viable seeds both on surface and buried at different depths in the soil.

In the subsequent sections, the sub-models added for describing multi-year grassland, mowing and mechanical weeding are described in detail.

2.1.2. The multi-year grassland sub-model

To date, ALOMYSYS only worked with annual crops. The introduction of temporary grassland into ALOMYSYS required adapting various submodels to the persistence of a sown crop cover over several years. There are no changes necessary for the sowing of the perennial crop; its emergence is modelled according to Donatelli and Marchetti (Donatelli and Marchetti, 1994), just as for any annual crop. Blackgrass seedlings emerging before the crop are only affected by intra-specific competition. Seedling mortality is governed by a density-dependent function described by Colbach *et al.* (2007). After crop emergence, the crop density is also integrated in this function. Because of these density-dependent mortality functions, the later the blackgrass plants emerge in simulated grassland, the less chance they have to survive because of the crop cover and earlier-emerging weeds. Simulations showed that during the subsequent years of grassland cover, survival rates for newly emerged blackgrass seedlings are reduced by approximately 50% or more, depending on the crop and weed densities, because of the already-existing crop cover.

The subsequent growth and development of the few surviving seedlings in perennial crops is assumed to be similar to that in annual winter crops. The main difference occurs at seed shed: in annual crops, the newly produced weed seeds fall on bare or sparsely covered soil, whereas in perennial crops, the seeds are shed on a closed and growing canopy. Many seeds are therefore lost before reaching the soil seed bank. Consequently, in grassland, only 21% of the produced seeds are added to the seed bank (based on data from Walker *et al.*, 2004 who compared seedling emergence of volunteer and weed seeds broadcasted on grassland vs. bare soil).

A second important difference between annual and multi-annual crops is the possibility of several harvest (without destroying the crop) or mowing operations each year in the latter. Mowing operations are though not specific to multi-annual crops but can also occur in setaside.

2.1.3. The mowing sub-model

The data for the equations describing the effects of mowing were taken from previous studies (Dalbiès-Dulout, 1999; Dalbiès-Dulout and Doré, 2001). These authors analysed yield components (i.e. number of tillers and heads per plant, number of flowers per head, rate of flowers with a viable seed) and the dates of flowering and seed production of blackgrass plants, depending on mowing dates (ranging from stages 59 to 80, Zadoks *et al.*, 1974) and frequency (none, once, twice), in different years and locations, both in greenhouse and in field experiments.

2.1.3.1 Plant mortality

Dalbiès-Dulout and Doré (2001) did not report any mortality after mowing for plants cut up to maturity onset. The tillers of existing plants were destroyed, but the plants survived to produce new tillers, heads, flowers and seeds. Based on expert opinion, mortality was added in ALOMYSYS for late-cut plants that have already started to produce seeds and have less assimilates available for growing new tillers. Thus, plants that present at least one mature head (i.e. with seeds starting to shed) when cut do not survive but their seeds are added to the seed bank.

2.1.3.2 Flowering and maturity dates

Dalbiès-Dulout (1999) monitored the dates of flowering and maturity onset in greenhouse and in field trials on blackgrass plants, depending on mowing date and frequency. She found that these factors did not affect the time between mowing and flowering and between mowing and maturity. In ALOMYSYS, flowering of cut plants therefore occurs 368 °C·days (base temperature 0°C) after the last mowing date, the onset of head maturation is fixed at 986 °C·days after the last mowing date. Only plants cut less than 368 °C·days before the theoretical flowering date are considered to be tall enough to be affected by mowing and have their subsequent growth, development and seed production modified.

2.1.3.3 Tillering and head production

In ALOMYSYS, the rates of new tillers and new heads (in fact inflorescences) appearing per unit time remains unchanged by mowing as well as the maximum possible tillers per plant in a given crop environment. With uncut plants, the model uses the foliar time since seedling emergence (*i.e.* the thermal time since emergence divided by the phyllochrone, the latter being the thermal time between the emission of two successive leaves on the main tiller), with an initial lag of 3 (*i.e.* no tillers emerge

before the plant has produced 3 leaves). With cut plants, the thermal time since the last mowing is used instead, without initial lag.

2.1.3.4 Number of flowers per head

When comparing cut vs. uncut plants, Dalbiès-Dulout and Doré (2001) observed a considerable decrease in head lengths, a variable strongly related to the number of flowers (in fact spikelets) per head (Chauvel *et al.*, 2000; Dalbiès-Dulout and Doré, 2001). For very early cut plants, they though reported slight increases in head lengths. ALOMYSYS first calculates the number of flowers per head **FH** at seed shed for both uncut and cut plants as a function of blackgrass density, crop type and available nitrogen, using the equations from the initial version (Colbach *et al.*, 2007). Then, **FH** is multiplied for cut plants by a corrective factor based on an analysis of covariance of head lengths of cut vs. uncut plants from Dalbiès-Dulout and Doré (2001):

$$\text{variation}_{\text{FH}} = 1.62 - 0.000729 \cdot \text{mowing date} + \text{error} \quad r^2 = 0.52 \quad [1]$$

with the date of the last mowing (in °C-days since weed emergence) before seed production. The other tested explanatory variables, i.e. mowing frequency, the trial location (field vs. greenhouse) and the weed density were not significant at $\alpha = 0.05$.

2.1.3.5 The rate of flowers with a viable seed

Blackgrass is a strictly allogamous plant (Johnsson, 1944; Naylor, 1972) and flowers often produce empty seeds. In ALOMYSYS, the rate of flowers with a viable seed **SF** is calculated at seed shed for both uncut and cut plants, as a function of crop type and blackgrass density (Colbach *et al.*, 2007). Again, a corrective factor is used for cut plants, based on data from the greenhouse trial from Dalbiès-Dulout and Doré (2001):

$$\text{variation}_{\text{SF}} = 1.03 + \text{effect}_{\text{mowing frequency}} + \text{error} \quad r^2 = 0.99 \quad [2]$$

where $\text{effect}_{\text{mowing frequency}} = 0.5$ and -0.5 for one and two mowings, respectively. The date at which the plants were cut did not influence their subsequent seed viability rate.

2.1.4. The mechanical weeding sub-model

ALOMYSYS distinguishes two types of mechanical weeding operations: hoeing and harrowing. Hoeing is used in large-interrow crops (e.g. sugar beet, maize) and applied solely to the inter-row area (of which the width is chosen by the user) where it (1) uproots all emerged seedlings and (2) covers them with soil. Harrowing is used in cereals and other narrow-row crops and is applied to the whole field, including the crop rows but is less efficient in destroying weeds. It only partially uproots and covers germinated seeds and emerged seedlings. In ALOMYSYS, these functions were based on Kurstjens' laboratory work on sandy soil with *Lolium perenne* (Kurstjens and Perdok, 2000; Kurstjens *et al.*,

2000). *L. perenne* was the only grass species studied by Kurstjens *et al.* and its seedlings are likely to respond similarly to *A. myosuroides*.

Whatever the tool, the resulting mortality rate of the weeds and the decrease in growth of the surviving weeds then depends on whether the plants were uprooted and/or covered as well as on environmental conditions and various characteristics of the weeding operation. These processes were based on laboratory experiments by Kurstjens and Kropff (2001).

In addition, hoeing and harrowing affect soil structure, mix the seeds of the tilled layers and trigger germination of the non-dormant seeds located in these layers of the tilled area. These sub-models for these effects are described by Colbach *et al.* (2006b).

2.1.4.1 *The rate of uprooted plants by harrowing and the leaf area covered by soil*

Kurstjens *et al.* (2000) measured the rate of uprooted plants after harrowing in different soil moisture conditions as a function of tillage characteristics (i.e. working depth, in mm, and speed, in m·s⁻¹). In the present paper, a linear model was fitted to describe the uprooting rate as a function of these variables and of foliar time, keeping only variables significant at alpha = 0.05 in the final model (PROC GLM of SAS, weighting sum of squares by the number of seedlings in each leaf stage class). To facilitate the use of the resultant model in soil textures other than the sandy soil used in the experiment, soil water potential (MPa) was preferred to soil moisture and was estimated from the soil moisture measured at harrowing using data from Kurstjens (2002), fitting van Genuchten's equation relating soil water potential and moisture (Van Genuchten, 1980). Foliar time **LP_{de}** was deduced from the plant size actually measured in Kurstjens' experiments by assuming the tallest plants (i.e. 50 mm) to have reached the one-leaf stage and germinated but un-emerged seeds at zero leaf:

$$\begin{aligned} \log_e(\text{uprooting rate}_{de}+1) = & 0.0155 - 0.0215 \cdot \log_e(-\text{water potential}) \\ & + 0.0853 \cdot \log_e(\text{working speed}) \\ & + 0.156 \cdot \log_e(\text{working depth}) \\ & - 0.703 \cdot \log_e(\mathbf{LP}_{de}+1) \\ R^2 = & 0.73 \end{aligned} \quad [3]$$

Uprooting increased with working depth and speed, but decreased with soil dryness (i.e. – *water potential*) and with foliar time. Consequently, the older the seedlings, the less sensitive they are to mechanical weeding. When introduced into ALOMYSYS, restrictions were added to equation [3] to keep the uprooting rate within [0, 1]. For yet un-emerged seedlings, i.e. germinated seeds, the same equation is applied to calculate uprooting rate, with **LP_{de}** = 0.

In the same experiment, Kurstjens and Perdok (2000) also measured the relative leaf area covered by soil immediately after harrowing and these data were also fitted with a linear model:

$$\begin{aligned} \log_e(\text{rate of covered leaf area}_{de}+1) = & 0.0110 + 0.0184 \cdot \log_e(-\text{water potential}) \\ & + 0.356 \cdot \log_e(\text{working speed}) \\ & + 0.127 \cdot \log_e(\text{working depth}) \end{aligned} \quad [4]$$

$$-0.162 \cdot \log_e(\mathbf{LP}_{de} + 1)$$

$$r^2 = 0.67$$

The drier the soil (i.e. the larger $\log(-\text{water potential})$), the deeper and the faster the harrowing operation, the more the seedlings were covered by soil after harrowing. In addition, leaf coverage decreased with foliar time, i.e. the larger the plants the less they were covered by soil. Restrictions were added to equation [4] to keep the covering rate within [0, 1].

2.1.4.2 *Survival and growth reduction rates of uprooted and non-uprooted plants*

Kurstjens and Kropff (2001) measured the survival rate of uprooted and non-uprooted plants after harrowing, as well as the reduction of growth (i.e. plant biomass relative to plants that were neither uprooted or covered) of the surviving plants. Their data were analysed here with a linear model using soil water potential, working depth and speed as explanatory variables. Only variables and interactions significant at $\alpha = 0.05$ were kept in the final model:

$$\begin{aligned} \text{For non-uprooted plants:} \quad & \text{survival rate}_{de} = 0.960 - 0.0322 \cdot \log_e(-\text{water potential}) \\ & - 0.179 \cdot \log_e(\text{working speed}) \\ & - 0.0449 \cdot \log_e(\mathbf{LP}_{de} + 1) \end{aligned}$$

$$\begin{aligned} \text{For uprooted plants:} \quad & \text{survival rate}_{de} = 0.960 - 0.120 \cdot \log_e(-\text{water potential}) \quad [5] \\ & - 0.179 \cdot \log_e(\text{working speed}) \\ & - 0.156 \cdot \log_e(\text{working depth}) \\ & - 0.396 \cdot \log_e(\mathbf{LP}_{de} + 1) \end{aligned}$$

$$R^2 = 0.84$$

Even apparently undisturbed, i.e. non-uprooted, plants were affected by harrowing though their survival was considerably higher than for uprooted plants (i.e. a mean survival of 92% vs. 45%). For both uprooted and non-uprooted plants, survival increased with water potential and decreased with working speed. In addition, survival of uprooted plants also decreased with working depth and leaf stage. Similar relationships were found for the relative plant weight of surviving plants after harrowing:

$$\begin{aligned} \text{For non-uprooted plants:} \quad & \log_e(\text{relative weight}_{de}) = 0.103 + 0.0691 \cdot \text{water potential} \\ & - 0.0475 \cdot \text{leaf cover rate}_{de} \quad [6] \end{aligned}$$

$$\begin{aligned} \text{For uprooted plants:} \quad & \log_e(\text{relative weight}_{de}) = 0.103 + 1.880 \cdot \text{water potential} \\ & - 0.737 \cdot \text{leaf cover rate}_{de} \end{aligned}$$

$$R^2 = 0.53$$

The drier the soil and the more soil on the seedlings, the more the relative weight of the surviving seedlings decreased. Effects were stronger for uprooted vs. non-uprooted seedlings. Restrictions were added to equations [5] and [6] to keep the survival and weight rates within [0, 1] after introduction into ALOMYSYS.

2.1.4.3 Seedling mortality and growth reduction

The final effects of harrowing and hoeing depend on whether plants are uprooted and/or covered by soil and result from combining the previous 4 equations, here for instance for survival of emerged seedlings:

$$PM2_{de} = PM2_{d-1e} \cdot (\text{uprooting rate}_{de} \cdot \text{survival rate}_{de}[\text{uprooted}] + (1 - \text{uprooting rate}_{de}) \cdot \text{survival rate}_{de}[\text{non-uprooted}]) \quad [7]$$

$PM2_{de}$ is the number of plants per m^2 present on day d and having emerged on day e . For harrowing (or any other tools working both crop rows and interrows), the survival rates are applied to all emerged seedling cohorts as well as germinated seeds located in the layers tilled by the harrow. Figure 1 shows that plant survival decreases with harrowing speed and depth as well as soil dryness and plant stage at harrowing.

The growth reduction rate is used to calculate the decrease in tillering for each seedling cohort by decreasing the maximum possible tiller number in a given crop environment (see chapter 2.1.3.3). The rate of tillers with a head, the number of flowers per head and the rate of flowers with a viable seed were also multiplied by the growth reduction rate. Figure 1 shows that post-harrowing weed growth decreased with working speed and depth as well as soil dryness whereas it increased with plant stage.

For hoeing and other tools that only work the interrow area, the field is divided into two subunits, the crop row and the interrow unit. The relative area of the latter unit is chosen by the user (e.g. 70% of total field area). Survival rates are only applied to seedlings and seeds located in the interrow area. Thus, part of the seedlings are unaffected even by multiple weeding operations and constitute the largest weeds producing most seeds at crop harvest. The effect on tillering, flowers per head and seeds per flower was though not spatialized explicitly (i.e. by calculating separate values for row and interrow plants) to limit necessary computer power and simulation length but resulted from the weighted contributed of row and interrow plants, here for instance for the maximum flowering rate m_{de} :

$$m_{de} = m_{d-1e} \cdot (PM2_{de}[\text{row}] \cdot 1 + PM2_{de}[\text{interrow}] \cdot (\text{uprooting rate}_{de} \cdot \text{relative weight}_{de}[\text{uprooted}] + (1 - \text{uprooting rate}_{de}) \cdot \text{relative weight}_{de}[\text{non-uprooted}])) \quad [8]$$

2.2. Simulations

The objective was to test scenarios for converting a standard herbicide-based reference cropping system into an alternative system without any herbicide applications. The alternative scenarios were based on mechanical weeding, mowing and the introduction of multi-year grass land. These techniques were first evaluated individually to identify those of their characteristics mostly influencing weed control. In a second step, comprehensive cropping systems were tested, looking at short, medium and long-term weed control. Statistical analyses not only looked at mean differences between systems,

but particularly focused on probabilities of obtaining better weed control and on risks of long-term weed increase. Evaluation though only concerned weed control, to the exclusion of more general agronomic, organisational or economic criteria.

2.2.1. The reference system

The reference herbicide-base system was a winter oilseed rape (OSR) / winter wheat (WW) / winter barley (WB) rotation, identified as the most common rotation in farm surveys carried out in Côte d'Or, Burgundy (Eastern France) (Colbach *et al.*, 2008). The sowing dates and densities used in the simulation were obtained by averaging actual dates and densities noted for this rotation in the surveys; the same method was used for choosing simulated nitrogen fertilization and harvest (Table 2). The herbicide programme and tillage strategies were those most frequently observed for the OSR/WW/WB rotation. Herbicides were always carried out at optimal conditions and times and achieved the maximum efficiency rate of the product. A slightly modified reference system (called R') was tested where optimal application conditions were only achieved in two years out of three, thus leading to a reduced herbicide efficiency (e.g. 97% instead of 100% for grass-targeting herbicide, based on Mamarot and Rodriguez, 2003).

Simulations started with an initial blackgrass emergence of 100 plants/m² during the crop season and lasted for 27 years. Ten repetitions were carried out for each reference system, by randomly choosing each year annual climate scenarios from weather series from 1986 to 2004 recorded at the meteorological station located at the INRA experimental station at Dijon, France (5°2'E, 47°20'N). The associated soil climate variables were estimated with the soil-crop model STICS (Brisson *et al.*, 1998b; 2002).

2.2.2. Single mechanical weeding tactics

The objective was to analyse the effect of weeding characteristics (i.e. tool, date, weeded area, working depth and speed) on weed densities at different stages in two crops, either OSR or WW. If hoeing was carried out in WW, interrow width had to be increased, leading to a decrease in sowing density of approximately 25%. The simulations of the weeding scenarios started at the harvest of the previous crop and lasted until the harvest of the analysed crop. The initial seed bank and soil structure at the simulation onset were those left after six (when looking at mechanical weeding in OSR) or seven years (in WW) of the reference system, using median values of seed densities and soil clod distributions from the 10 repetitions of the reference system. There was also one unweeded control scenario. Each scenario was repeated ten times, with the same ten random weather series that were used for the reference system.

The effect of weeding tools and dates on weed infestation at OSR harvest simulated by ALOMYSYS was analysed with linear models, using the GLM procedure of SAS:

$$\log_e(\text{ALOMYSYS output}_{ij}) = \text{constant}$$

$$\begin{aligned}
& + tool_i \\
& + repetition_j \\
& + a \cdot \log_e (weeding\ date) \\
& + b_i \cdot \log_e (weeding\ date) \\
& + error_{ij} \qquad \qquad \qquad [9]
\end{aligned}$$

with i being either hoe or harrow and the repetition indicator $j \in \{1, \dots, 10\}$. Weeding dates are in number of days since sowing. $Tool_i$ and $repetition_j$ are qualitative variables, weeding date a quantitative variable studied both as primary factor (coefficient a) and in interaction with the tool (coefficient b_i). The analysed ALOMYSYS output were plant survival after weeding, mature weeds at crop harvest, weed seed production and pre-harvest seed bank (before the new seed rain). The other characteristics (i.e. area, depth and speed) were analysed, with comparisons of means, using least significant difference tests, after an analysis of variance using the scenario and the repetition as factors.

2.2.3. Multiple weeding scenarios

Based on the previous results, a large range of weeding scenarios was compared (see list in Table 3). In addition to the single weeding scenarios analysed previously in OSR, various double and triple scenarios tested different combinations of hoeing and harrowing, with different autumn and spring timings. In WW, there was more emphasis on harrowing which is the more usual tool in WW. In all scenarios, the same simulation protocol as for single weeding tactics was used. For each crop, scenarios were ranked with comparisons of means, using least significant difference tests, after an analysis of variance using the scenario and the repetition as factors.

2.2.4. Alternative scenarios with tri-annual grassland and mowing

The effects of mowing dates and frequencies were tested during a three-year simulation with lucerne, starting with the seed bank and soil structure left after a six-year OSR/WW/WB simulation. The other cultivation techniques used to managed lucerne was based on the Côte d'Or farm surveys (Colbach *et al.*, 2008). The crop was thus sown without prior tillage on 22 July, with its final harvest on 14 July three years later. Each mowing scenario (see list in Table 4) was repeated ten times, with the same randomly chosen weather series. The seed bank left by the different mowing scenarios after the lucerne harvest (including the last seed rain) was compared, using least significant difference tests, after an analysis of variance using the scenario and the repetition as factors.

2.2.5. Long-term evaluations of the alternative scenarios

The best mechanical weeding options for each crop type (i.e. OSR and cereals) were combined and simulated over the years, starting with a 100-plant emergence at the first year and the same ten random

27-year-long weather combinations as for the reference simulation. If the alternative scenario was better than the reference (i.e. less infestation than the reference in at least one repetition, never any higher infestation), less stringent weeding options could be tested in the least-risky crops to reduce work and constraints for farmers. Conversely, if the alternative scenario was worse than the reference, additional management options were tested, starting with the most influential cropping system components, i.e. rotation and tillage (Chauvel *et al.*, 2001).

Three criteria were used for comparing the scenarios: the short-term infestation (the density of mature plants averaged over the first three years of the simulation), the medium-term infestation (the same over years 13-15), and the long-term risk (i.e. the correlation between weed densities and years 13-26). For each repetition $j \in \{1, \dots, 10\}$, the initial and medium-term infestations of the alternative scenarios were compared with the reference, using the following linear model:

$$\begin{aligned} \text{weed density}_{ijk} = & \text{constant} \\ & + \text{scenario}_i \\ & + \text{crop}_k \\ & + \text{error}_{ijk} \end{aligned} \quad [10]$$

with $k \in \{1, 2, 3\}$ (initial infestation) or $\{13, 14, 15\}$ (medium-term infestation). The scenario_i values of each alternative scenario i were then compared to the reference value scenario_0 and the number of repetitions where the infestation of the alternative scenario exceeded the reference scenario was determined. Long-term progress was analysed with Spearman correlations (PROC CORR Spearman of SAS) between weed densities and years for each scenario and repetition and the number of repetitions with a significant positive correlation calculated.

A second series of multi-year simulations consisted in introducing either three or six years of continuous lucerne into the OSR/WW/WB rotation management, alternating with either three or six years of annual crops, respectively. Grassland was managed with the best mowing strategy and the remaining crops with the best mechanical weeding strategy. There was no burial of former crop residues or manure before OSR if the previous crop was lucerne. Weed infestation was analysed with equation [10] and Spearman correlations.

3. Results

3.1. Short-term effects of mechanical weeding

3.1.1. Single mechanical weeding tactics

Plant mortality, weed density at crop harvest, weed seed production and surviving seed bank prior to seed rain all varied with the tool and date of mechanical weeding as well as with the crop (Figure 2). The analysis of the simulation results with linear model [9] showed that for weeding immediately

after crop sowing, harrowing was usually more effective than hoeing, i.e. less plants survived weeding and there were less mature weeds, seed production and surviving seed bank at crop harvest (Table 5). Indeed, harrowing tilled 100% of the field area compared to only 70% for hoeing. Moreover, interrow width had to be increased to allow hoeing, leading to a decrease in WW sowing densities, thus leaving more space for emerging weeds. Plant mortality after hoeing efficiency though increased with the lateness of the operation while the opposite was true for harrowing which did not uproot the larger weeds found later in season (see equation [3]). However, when looking at seed production, harrowing had better to be delayed until 2-3 weeks after sowing (Figure 2). Though the plant mortality rate was slightly lower at that date, more blackgrass seedlings had emerged and were affected by the weeding. Earlier weeding operations occurred before or at the onset of the weed emergence flush and could therefore not destroy the weed seedlings. The seed bank prior to the new seed rain always decreased with weeding date, because the weeding tool tilled the soil and triggered seed germination. In OSR, there was though no effect of early weeding on the seed bank because the soil was still too dry for the weeding tool to stimulate much germination.

Despite the inclusion of soil water potential effects in both uprooting and survival equations (see [3] and [5]), plant survival after weeding did not vary significantly between repetitions but mostly depended on weeding date (see partial R^2 in Table 5). The repetition factor, and therefore weather, significantly influenced the other three analysed weed variables, i.e. mature plants at harvest, seed production and seed bank before seed rain. The relevant weather variable here was soil water potential and its effect on seed germination and seedling emergence, thus influencing weed densities and seed production as well as surviving seeds in the soil.

Increasing harrowing speed significantly decreased plant survival though the subsequent effect on mature plants and seed production was slight and the effect on seed bank nil (Table 6). Increasing harrowing depth significantly decreased plant survival but mature plants and seed production were increased because of additional seed germination. Decreasing the width of the hoed interrow area and thus the relative hoed field area considerably increased plant survival and mature plants while seed production was almost doubled. The seed bank was also slightly increased because the narrower hoeing triggered less seed germination.

3.1.2. Weeding strategies in oilseed rape

Based on these results, a large range of weeding scenarios were tested. The tested scenarios were ranked according to their seed production (Table 3.A). This variable was thought to synthesize both immediate (seed production is related to weed biomass which causes yield loss) and long-term risks (future infestations). Triple scenarios were best for controlling blackgrass seed production, but only if the last operation in spring was carried out with a hoe. These scenarios divided seed production by nearly 15 compared to the unweeded control. The best triple scenarios were those without harrowing

or with early harrowing. The later the hoeing operations in the triple scenarios, the better while the opposite was true for harrowing.

The sextuple harrowing was nearly as good as the best triple scenario. Double scenarios performed less well than most triple scenarios. Again, any scenarios with late hoeing were best. Single late autumn hoeings were as good as triple or double harrowings. Any other single scenarios presented little efficiency though all reduced seed production relative to the unweeded control.

The ranking of the various scenarios for their effect on the seed bank prior to seed rain was not entirely the same as the ranking obtained for seed production control. Generally, the more operations the less seeds survived because of germination triggering. Harrowing triggered more germinations than hoeing because of the larger tilled area. The sextuple harrowing reduced seed bank by approximately 30% compared to the control.

3.1.3. Mechanical weeding in winter wheat

Table 3.B lists the weeding scenarios tested in WW. The general ranking of the scenarios was slightly different to that observed for OSR, with the sextuple harrowing being the best option. The date of the first operation was a very important factor, with scenarios starting weeding three weeks after sowing (30 Oct.) performing best. Double scenarios ranked better than in OSR as in WW, double scenarios finished with a spring weeding, in contrast to double OSR strategies.

3.2. Mowing in tri-annual lucerne

The worst scenarios in lucerne were those with a single mowing (Table 4). Among these, mowing in mid-June was the best option. Advancing the mowing operation to mid-May more than doubled the seed bank because too many blackgrass plants survived to produce seeds later. Delaying mowing to mid-July multiplied the seed bank by 4 because seed shed had already started at that date. Later mowing dates were as bad as the unmown scenario because seed maturation was nearly finished.

Double and, even better, triple mowings considerably improved blackgrass control though the efficiency again varied with the mowing dates relative to seed production. Thus, among the double mowing strategies (which all started with a first mowing in mid-May), a too early second mowing (before mid-June) more than tripled the final seed bank compared to a second mowing in mid-June while too late mowing (after July) multiplied it by 30. Among the triple mowings, the best option was mowing every 4-6 weeks, starting in mid-May. Starting mowing only at the end of May multiplied the seed bank by nearly 4.

3.3. Evaluation of long-term non-chemical weed management

Considering the results of the annual simulations on seed production and seed bank (both responsible for long-term infestation), the best multi-year option should consist of triple hoeing in OSR (one and two months after sowing and another in April) and sextuple harrowing in winter wheat (hence the M1

scenario). A slightly less efficient scenario would consist in triple hoeing in all crops which would reduce the workload for the farmer.

During the first years of the multi-year simulation, the blackgrass infestation in these two scenarios was 2-3 times higher than in the herbicide-based reference scenario R (Table 7). Over time, the difference between the alternative and the reference scenarios increased considerably (Figure 3). At medium-term, M1 and M2 exceeded the reference scenario in all repetitions, with the highest weed densities in M2 (Table 7) as triple hoeing in cereals was shown to control seed production less well than sextuple harrowing (Table 3.B). At long term, the R and M2 scenarios presented stable or decreasing infestations as their mean Spearman correlation coefficient was lower than zero (pointing to a decrease in weed densities with time) and in none of the ten repetitions significantly higher than zero. The long-term M1 dynamics were slightly less stable as infestations significantly increased in one of the repetitions.

As the M1 and M2 strategies did not manage to keep infestations at a low and stable level, the idea of the L1 scenario was to diversify the rotation by introducing a three-year lucerne managed with the optimal mowing strategy identified in Table 4 (i.e. mowing thrice every year at 4-6 weeks intervals, starting in mid-May), resulting in a six-year rotation OSR/WW/WB/3-year lucerne. The infestation during the lucerne was close to zero though it again soared during the three years of annual crops (Figure 3). Indeed, the blackgrass seeds survived quite well during the three years of lucerne where no tillage operations stimulated seed germination. Despite this high seed survival, infestations during the annual crops were divided by more than ten compared to the M1 scenario and slightly decreased over time. Medium-term infestations in the L1 scenario were though still higher than in the R scenario (Table 7). The infestation was even worse if the rotation alternated six years of annual crops and six years of continuous lucerne (L2 of Table 7). The slow seed bank depletion during the lucerne was not sufficient to compensate the increased weed seed production during the six continuous years of annual crops. To address this problem of insufficient seed bank reduction, the L3 scenario tilled the field before sowing the three-year lucerne to increase fatal seed germination. This strategy considerably decreased mid-term infestations though long-term dynamics became more unstable, i.e. in three out of ten repetitions, infestations increased significantly.

As seed bank management proved crucial for blackgrass control, the last series of multi-year simulations tested the introduction of mouldboard ploughing to both stimulate fatal seed germination and limit in-crop weed emergence. Ploughing each year before the annual crops (P1 scenario) was sufficient to reduce blackgrass to a level comparable to the herbicide-based R system though long-term dynamics were still unstable. As ploughing though requires more time and fuel than other tillage operations, the remaining three P scenarios only ploughed before either OSR, WW or WB. Though short-term infestation increased slightly, the reduced ploughing frequency was sufficient to control blackgrass at a level comparable to the reference systems, especially when ploughing before the

second annual crop, i.e. WW (P3 scenario). In that case, long-term dynamics became even more stable than in the P1 scenario.

4. Discussion

4.1. Modelling approach

The present modelling approach was based on a process-based representation of effects of techniques and their interactions with environmental conditions. These experimental data were preferred to synthetic observations from field trials (e.g. Rasmussen, 1992) because mechanical weeding and, to a lesser degree, mowing have complex and sometimes compensating effects (e.g. seedling mortality vs. triggering of seed germination by tillage) that interact with environmental conditions and weed stages. This approach could be taken because Kurstjens et al. set up detailed experiments to assess the various differential effects (e.g. uprooting, covering plants with soil) in interaction with environment (e.g. soil moisture), weeding characteristics (depth, speed) and weed stages. Similarly, Dalbiès-Dulout and Doré analysed the effect of mowing characteristics on the different stages and yield components of blackgrass. The addition of these various processes to the existing ALOMYSYS model was only possible because of its modular structure and its strong focus on a mechanistic representation of interactions. These characteristics also ease the addition of other weeding implements (e.g. Chicouene, 2007) and preventive tactics.

However, the disadvantage of this approach is the high number of required condition-specific relationships. This particularly holds for the mechanical weeding submodel. The effect of soil conditions and weed growth stage can only be separated by assessing the height or mass of individual weeds. The necessary data were taken from laboratory experiments because these are the only data on weed survival and growth reduction that are specific for weed size and types of damage as created by implements. Principally, data from artificial physical damaging experiments (Habel, 1954; Jones *et al.*, 1995; , 1996; Baerveldt and Ascard, 1999) could have been used as well in this approach, but the representativeness of the artificial damaging is very important though uncertain (Kurstjens and Kropff, 2001).

If condition-specific relationships could only be derived from laboratory experiments, the consistence with field conditions would be a principal weakness of the approach used here. In Kurstjens' laboratory experiments with homogeneous sandy soil and absence of rain, large uprooted plants had little chance of surviving. Their survival chance might be better in other, more clayey textures where, conversely, uprooting might work better in drier vs. moist conditions. The adaptation of the submodel parameters to other soil textures could be dealt with by additional experiments or expert opinion. The constant climate chamber conditions and the absence of rain in the laboratory experiments do not adequately represent field conditions. In real fields, the post-harrowing weather with its daily rhythms of temperature, wind, radiation and humidity governs the survival of uprooted seedlings. For instance,

root balls of large plants can reconnect to the soil after rain and thus survive better as predicted by the present model. The survival of large uprooted plants was therefore probably underestimated, especially as the experiments only worked with plants up to one leaf. However, assessing the effects of environmental conditions on weed dynamics in fields poses a more fundamental problem, because the observed plant survival and growth reduction are the result of various distinct processes that are difficult to discriminate and measure in fields. Consequently, highly conditioned laboratory experiments play a crucial role.

To orientate future attempts for evaluating and improving the model, analysing the sensitivity of the model output to the various parameters describing the effects of the newly added techniques would be helpful. The authors are presently working on a series of virtual experiments with contrasted cropping systems where the model parameters are made to vary randomly, using techniques of sensitivity analyses already applied to other complex cropping system models (e.g. Colbach *et al.*, 2009).

4.2. Preliminary model evaluation

The simulations of mechanical weeding operations showed low efficiency of weed harrow expressed as percentage of seedling killed, even for early harrowings (and thus young seedlings). This is in accordance with experimental data of Kurstjens and Kropff (2001) who reported mortalities ranging from 10 to 30 % for the grass weed *Lolium perenne*. The efficiency though varies considerably with the tool and the seedling stage at weeding. For instance, Kurstjens (2007) reported efficiencies of intra-row mechanical weeding reaching up to 70% for young seedlings, just as for late hoeing in the present simulations. French extension services report similar weeding efficiencies on their multi-local field experiment for very young grass weed seedlings just after emergence (first leaf not yet fully expanded). This mortality rate is indeed higher than the one obtained here when evaluating the weeding tactics and scenarios. However, the model sensitivity analysis showed plant survival to vary considerably with harrowing characteristics and conditions; it moreover predicted plant mortality rates similar to those observed by the extension services for very young plants or faster and deeper harrowing. In the simulations, seedling populations though consisted of both young and older plants with the latter surviving quite well after harrowing. In addition, weeding operations were simulated at fixed and not necessarily optimal dates whereas in field experiments, the timing of the operations was optimised relative to soil moisture.

The frequency and timing of mowing relative to weed stages, particularly the onset of seed production, was crucial in the present simulations. There are only a few reports in literature on the impact of cutting on blackgrass. As in the present simulations, Meiss *et al.* (2008) reported decreasing survival and biomass production with increasing plant stage at mowing. Conversely, Andreasen *et al.* (2002) did not observe any plant stage effect for the sole grass species they studied but they cut their plants very early, without much timing difference (i.e. 2 and 3-leaf stage, respectively), and only looked at short-term biomass production.

Though blackgrass decreased in rotations with 3-year lucerne, infestations in the annual crops were still high. This was, at first, surprising as temporary grassland is usually considered a weed-suppressing crop (Bellinder *et al.*, 2004; Teasdale *et al.*, 2004; Albrecht, 2005; Heggenstaller and Liebman, 2006). However, blackgrass seeds survive quite well in the absence of germination-triggering tillage and/or when buried at depths where germination is inhibited (Lonchamp *et al.*, 1984; Colbach *et al.*, 2006a). So even though blackgrass seed production is nil or negligible in perennial canopies, the seed bank left after the temporary grassland is still important. It is probable that the introduction into the rotation of spring crops (where blackgrass emerges and reproduces badly, Colbach *et al.*, 2007) might be more interesting because of frequent germination-triggering tillage operations.

Though these first comparisons to literature reports are encouraging, the submodels added here to ALOMYSYS must be evaluated with independent field data, to determine the conditions in which the model can be safely used, its prediction error as well as deficiencies that must be corrected in future. This evaluation should be conducted at two levels, just as in the simulations carried out here. In the case of mechanical weeding, annual trials should monitor weed survival and reproduction as well as environmental conditions in treatments combining different tools, working depths, soil moisture conditions etc. Multi-year cropping system trials should complete this analysis by looking at weed dynamics over several years, albeit with less detail and frequency. A similar approach was indeed used to evaluate the initial version of ALOMYSYS, looking in detail at weekly emergence in short-term trials (Colbach *et al.*, 2006a) and at multi-year dynamics in long-term cropping systems (Colbach *et al.*, 2007).

4.3. Implications for weed management

The simulations show that non-chemical weed control can neither be reasoned at short-term nor replace herbicides; when combined with other cultivation techniques, non-chemical weed control can though be as efficient as herbicide-based systems. In a long-term experiment testing cropping system prototypes based on Integrated Weed Management, mechanical weeding proved to be very useful in controlling blackgrass efficiently with little or no herbicides, provided that it was associated with a diversified crop rotation, stale seed bed techniques, delayed cereal sowing, competitive cultivars, high sowing densities, reduced inter-row distance, ... (Chikowo *et al.*, 2009). In the present study, only a limited number of strategies were tested for a single rotation typical of Burgundy, but practical conclusions can already be drawn for advising farmers. The good news for farmers is that well-reasoned mechanical weeding combined with other judiciously chosen modifications in the cropping system is viable at long-term and as good as herbicide strategies. The bad news is that inadequate timing of mechanical weeding or mowing can increase blackgrass infestation, not only because of insufficient control, but, in the case of mechanical weeding also because of subsequent germination and emergence flushes caused by the weeding tool. In addition, the diversification of the intensive

rotation by introducing a perennial legume crop (a frequent strategy in organic farming) was not as efficient as expected. Introducing spring crops preceded by stale seed bank techniques would be much more interesting for managing blackgrass (Chauvel *et al.*, 2001; Colbach *et al.*, 2007; Chauvel *et al.*, 2009).

The simulated efficiency of mechanical weeding control and other weed-relevant cultivation techniques could probably be improved if crop management was not considered as a fixed programme where operations are always carried out at the same date, irrespective of weather or soil conditions. Indeed, the present simulations showed that weather conditions have a large impact on weed control effectiveness. If the simulated operation timing depended on prevailing weather conditions, mimicking the decision making of farmers waiting for the good conditions to implement the mechanical weeding, weeding efficiency would increase and vary less between years. If decision-rule models (Bergez *et al.*, 2002; Keating *et al.*, 2003; Chatelin *et al.*, 2005) could be connected to ALOMYSYS to take account of practical guidelines (depending on weather, soil moisture and crop and weed growth stage) and trafficability restrictions. Simulations would thus be more robust and used to improve guidelines, to assess risks and associated costs (crop damage, hand weeding, future control demands).

Moreover, the present study focused on a single particular weed species, i.e. blackgrass, and cannot be extrapolated to other species. Indeed, mechanical weeding is thus more efficient for controlling broadleaved vs. grass species (http://www.agri02.com/_Documents/Telecharge/herse_etrille.pdf) whereas species with short-lived and/or easily germinating seeds will rapidly disappear in rotations with multi-year crops (Clay and Aguilar, 1998; Ominski *et al.*, 1999; Schoofs and Entz, 2000; Entz *et al.*, 2002; Porter *et al.*, 2003). Conversely, small plants (e.g. *Veronica* sp.) will not be affected by mowing though they often reproduce badly in taller crops (Meiss *et al.*, 2008). Consequently, the authors are presently working on extrapolating the ALOMYSYS model to a multi-specific weed flora (Gardarin *et al.*, ; Gardarin, 2008).

In this study, the weed management strategies were evaluated considering only their efficiency for short and long-term weed control. This criterion is obviously not sufficient for providing a comprehensive assessment of sustainability at the cropping system level. In some cases mechanical weeding can damage the crop and restrict the yield (Melander *et al.*, 2008) and therefore the economic performance of the system. Mechanical weeding and tillage both require energy inputs, and the diversification of the crop sequence with legume crops also affects the energy balance of the system and possibly greenhouse-gas emissions. These issues will have to be considered in further assessments of alternative weed management strategies designed from model simulations.

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Table 1. Effects of cropping system on the blackgrass life-cycle (density and timing of stages) as simulated by ALOMYSYS (Colbach *et al.*, 2006b; Colbach *et al.*, 2007).

Cropping system	Intermediate effect	Effect on blackgrass
Tillage	Soil structure Soil movements = f(soil structure)	Soil compaction increases mortality of germinated seeds Seed burial decreases germination and increases pre-emergent mortality due to insufficient seed reserve Seeds on soil surface germinate badly because of insufficient seed-soil contact Germinated seeds close to soil surface often die because the top soil dries faster Exposure of imbibed seeds to light if inverting tool Triggering of germination flush if the soil is tilled in moist conditions Destruction of germinated seeds, seedlings and plants
Crop	Choice of cultivation techniques	See effects of techniques Blackgrass emergence is higher in winter crops than in spring crops as the latter are sown when seed dormancy is highest. Yield components (plant survival, tillers/plant, heads/tiller, flowers/head, seeds/flower) are usually higher in winter vs. spring crops but flowering and maturation is faster in spring crops
Sowing date	Crop emergence date Date of last tillage	The earlier the weed seedlings emerge relative to the crop, the better they survive The later the last tillage, the more weed seeds have germinated already and are killed by the tillage
Sowing density	Crop density	Increases weed seedling mortality
Herbicides		Weed mortality = f(active ingredient, conditions) Weed mortality decreases with plant density, seed depth (for root-acting herbicides) and weed stage Decreases tillering on surviving plants
Nitrogen fertiliser		Increases flowers/head Increases primary dormancy; germination of newly produced seeds is spread over a longer period
Harvest		Destruction of all plants Addition of newly produced seeds to seed bank

Table 2.

Crop management in the herbicide-based reference system of the oilseed rape/winter wheat/winter barley rotation.

Cultivation technique	Oilseed rape	Winter wheat	Winter barley
Residues from previous crop	Buried	Exported	Buried
Manure	43 m ³ /ha à 7.5 kg N/m ³ (15 July)	None	None
Tillage	Chisel (15 July) 2 x covercrop (1 Aug.) Power harrow (15 Aug.) Spring tine (27 Aug.)	Chisel (15 Aug.) Chisel (10 Sept.) Spring tine (10 Oct.)	Covercrop (1 aug.) Chisel (21 Aug.) Spring tine (10 Sept.) Power harrow (8 Oct.)
Sowing date	27 Aug.	10 Oct.	8 Oct.
Sowing density (seeds/m ²)	56	344	330
Herbicides ¹	trifluraline (26 Aug.) napropamide (26 Aug.) clomazone + dimétachlore + napropamide (26 Aug.) quizalofop-éthyl isomère D (5 Oct.)	iodosulfuron-méthyl-sodium + mésosulfuron-méthyl (12 March) 24MCPA + fluroxypyr + clopyralid (5 April)	imazaméthabenz-méthyl (7 Nov.) isoproturon (7 Nov.)
Nitrogen fertiliser (kg/ha)	75 (15 Feb.) 75 (15 March)	65 (15 Feb.) 92 (15 March) 33 (16 April)	55 (15 Feb.) 65 (15 March)
Harvest date	12 July	18 July	2 July

Soil texture was 36% clay, 58% loam and 6% sand, with 1% of stones. Soil depth was 90 cm.

¹ Herbicides were never applied at the total regulatory rate, but usually at only 66-80% of the rate. Applications were carried out at optimal conditions and times and therefore still produced the maximum efficiency rate of the product.

Table 3. Ranking of the tested weeding scenarios for controlling blackgrass seed production and seed bank. Simulations with ALOMYSYS

A. Oilseed rape.

Weeding scenarios				Seed production (seeds/m ²)		Seed bank before seed rain (seeds/m ²)	
1 st operation	2 nd operation	3 rd operation					
Hoe	23 Sept.	Hoe	21 Oct.	Hoe	1 April	13650 n	242 h
Harrow						15417 n m	214 i
Harrow	9 Sept.	Hoe	23 Sept.	Hoe	1 April	15595 n m	247 h
Harrow	16 Sept.	Hoe	16 Sept.	Hoe	1 April	16203 n m	246 h
Harrow	16 Sept.	Hoe	23 Sept.	Hoe	1 April	16741 n m	244 h
Hoe	23 Sept.	Harrow	21 Oct.	Hoe	1 April	16979 n m	239 h
Harrow	23 Sept.	Hoe	21 Oct.	Hoe	1 April	18385 n m	238 h
Hoe	23 Sept.	Hoe	21 Oct.	Harrow	1 April	18762 n m	242 h
Harrow	23 Sept.	Harrow	21 Oct.	Hoe	1 April	21263 n m l	235 h
Hoe	23 Sept.	Hoe	21 Oct.			21749 n m l	272 g f
Hoe	9 Sept.	Hoe	23 Sept.			21972 n m k l	279 f
Harrow	23 Sept.	Hoe	21 Oct.	Harrow	1 April	23650 n m k l	238 h
Harrow	23 Sept.	Hoe	21 Oct.			27009 n m k l	265 g f
Harrow	9 Sept.	Hoe	23 Sept.			27292 n m k l	272 g f
Hoe	23 Sept.	Harrow	21 Oct.	Harrow	1 April	32775 n j m k l	239 h
Hoe	9 Sept.	Harrow	23 Sept.			37563 j m k l	277 g f
Hoe	23 Sept.	Harrow	21 Oct.			42413 j k l	269 g f
Hoe	21 Oct.					44654 j i k	277 g f
Hoe	24 Nov.					50835 j i h	272 g f
Harrow	23 Sept.	Harrow	21 Oct.	Harrow	1 April	53304 j i g h	236 h
Hoe	1 April					54201 j i g h	273 g f
Hoe	23 Sept.					55139 j i g h	311 e d
Harrow	9 Sept.	Harrow	23 Sept.			67178 f i g h	271 g f
Hoe	16 Sept.					68714 f g h	333 b c
Harrow	23 Sept.	Harrow	21 Oct.			75574 f g	263 g
Hoe	9 Sept.					87116 f e	348 b a
Harrow	16 Sept.					101134 e d	321 d c
Harrow	9 Sept.					102498 e d	335 b a c
Harrow	23 Sept.					103759 e d	302 e
Hoe	2 Sept.					111968 c d	351 a
Harrow	2 Sept.					121633 c b d	337 b a c
Harrow	1 April					133555 c b	273 g f
Harrow	21 Oct.					139342 b	269 g f
Harrow	24 Nov.					142724 b	268 g f
Control						188208 a	341 b a

Means of a given column followed by the same letter are not significantly different at alpha = 0.05 (Analysis of variance with scenario and repetition factors followed by least significant difference test).

B. Winter Wheat

Weeding scenarios			Seed production (seeds/m ²)		Seed bank before seed rain (seeds/m ²)	
1 st operation	2 nd operation	3 rd operation				
Harrow			13890	v	551	n
Hoe 30 Oct.	Hoe 1 March	Hoe 1 April	22838	v u	552	n
Hoe 30 Oct.	Harrow 1 March	Hoe 1 April	24978	u	638	l m
Harrow 30 Oct.	Hoe 1 March	Hoe 1 April	29504	u t	804	h g
Hoe 30 Oct.	Hoe 1 March	Hoe 1 April	29885	u t	553	n
Hoe 30 Oct.	Hoe 1 March		30794	s u t	552	n
Harrow 30 Oct.	Harrow 1 March	Hoe 1 April	31228	s u t	813	h g
Harrow 30 Oct.	Hoe 1 March	Harrow 1 April	39043	s r t	808	h g
Harrow 30 Oct.	Hoe 1 April		40708	s r	686	k l m
Harrow 30 Oct.	Hoe 20 Nov.		43857	r q	673	l m
Harrow 30 Oct.	Hoe 1 March		45962	p r q	733	k j
Harrow 30 Oct.	Hoe 19 Feb.		46470	p r q	688	k l
Harrow 23 Oct.	Hoe 20 Nov.		46984	p r q	644	l m
Harrow 30 Oct.	Harrow 30 Nov.	Harrow 1 April	53826	p o q	779	h i j
Hoe 30 Oct.	Harrow 1 March	Harrow 1 April	56033	p o n	639	l m
Harrow 30 Oct.	Harrow 1 March	Harrow 1 April	63617	m o n	817	h g
Hoe 1 April			65633	m n	630	m
Harrow 23 Oct.	Harrow 20 Nov.		65838	m l n	646	l m
Harrow 30 Oct.	Harrow 20 Nov.		70974	K m l	736	k i j
Hoe 20 March			73820	K m j l	571	n
Hoe 19 Feb.			75942	K j l i	568	n
Hoe 5 March			77546	K h j i	570	n
Harrow 30 Oct.	Harrow 1 April		80233	K h j g i	790	h i
Harrow 19 Feb.	Harrow 10 March	Harrow 1 April	81576	h j g i	137	o
Harrow 30 Oct.	Harrow 1 March		84842	h g i	800	h
Harrow 30 Oct.	Harrow 19 Feb.		87518	h g	792	h i
Hoe 30 Oct.			88707	g	571	n
Harrow 23 Oct.			106557	f	922	e
Harrow 30 Oct.			107033	f	1041	c
Hoe 23 Oct.			110901	f	570	n
Harrow 1 April			133225	e	1252	a
Harrow 20 March			138801	e	984	d
Harrow 16 Oct.			143144	d e	1121	b
Harrow 5 March			149216	d c	906	f e
Harrow 19 Feb.			153328	d c	857	f g
Hoe 16 Oct.			153765	c	572	n
Control			177374	b	1252	a
Hoe 30 Oct.	Harrow 1 April		210222	a	634	l m

Means of a given column followed by the same letter are not significantly different at $\alpha = 0.05$ (Analysis of variance with scenario and repetition factors followed by least significant difference test).

Table 4. Ranking of the tested mowing scenarios for controlling blackgrass seed bank left after three years of lucerne.

Scenario (mowing dates)	Blackgrass seed bank (seeds/m ²)	
Triple mowing (mid-May, early July, mid-August)	1266	d
Triple mowing (mid-May, mid-June, mid-July)	1274	d
Double mowing (mid-May and mid-July)	1819	d
Double mowing (mid-May and mid-June)	1946	d
Triple mowing (late May, late June, late July)	4292	d
Double mowing (mid-May and early June)	7391	d
Single mowing (mid-June)	25042 c	d
Double mowing (mid-May and mid-August)	66327 c	b
Single mowing (mid-May)	66509 c	b
Single mowing (mid-July)	108737	b
Control (no mowing)	176453	a
Single mowing (mid-August)	178004	a

Means followed by the same letter are not significantly different at alpha = 0.05 (least significant difference test).

Table 5. Effect of weeding tool and date on weed survival and reproduction. Results of linear regression [9]

A. Oilseed rape

Weed stage		Factor		Weeding date		Repetition	R ²
		Hoe tool _{hoe}	Harrow tool _{harrow}	Hoe a+b _{hoe}	Harrow a+b _{harrow}		
Plant survival after weeding (plants/plants)	Regression coefficient	0.13	-0.13	-0.12	0.022	ns	
	<i>Partial R²</i>	0.12		0.78		0.00	0.90
Mature weeds at crop harvest (plants/m ²)	Regression coefficient	0.33	-0.33	-0.23	0.054	nl	
	<i>Partial R²</i>	0.09		0.29		0.53	0.91
Seed production (seeds/m ²)	Regression coefficient	0.27	-0.27	-0.25	0.066	nl	
	<i>Partial R²</i>	0.025		0.17		0.71	0.90
Seed bank before seed rain (seeds/m ²)	Regression coefficient	0.013	-0.013	-0.90		nl	
	<i>Partial R²</i>	0.003		0.14		0.79	0.93

B. Winter wheat

Weed stage		Factor		Weeding date		Repetition	R ²
		Hoe tool _{hoe}	Harrow tool _{harrow}	Hoe a+b _{hoe}	Harrow a+b _{harrow}		
Plant survival after weeding (plants/plants)	Regression coefficient	0.22	-0.22	-0.14	0.030	ns	
	<i>Partial R²</i>	0.18		0.74		0.00	0.92
Mature weeds at crop harvest (plants/m ²)	Regression coefficient	0.37	-0.37	-0.26	ns	nl	
	<i>Partial R²</i>	0.10		0.43		0.38	0.91
Seed production (seeds/m ²)	Regression coefficient	0.32	-0.32	-0.20	0.060	nl	
	<i>Partial R²</i>	0.09		0.34		0.43	0.87
Seed bank before seed rain (seeds/m ²)	Regression coefficient	0.060	-0.060	-0.092	-0.070	nl	
	<i>Partial R²</i>	0.003		0.11		0.87	0.97

All density variables and weeding dates were log_e-transformed prior to analysis. The tested regression was $\log_e(\text{ALOMYSYS output}_{ij}) = \text{constant} + \text{tool}_i + \text{repetition}_j + a \cdot \log_e(\text{weeding date}) + b_i \cdot \log_e(\text{weeding date}) + \text{error}_{ij}$, with i being either hoe or harrow and the repetition indicator $j \in \{1, \dots, 10\}$.

Working depth was 2 cm, working speed 2.5 m/s and hoed area was 0.7.

ns: not significant at alpha = 0.05

nl: regression coefficients not listed

Table 6. Effect of weeding depth, speed and area on blackgrass infestation in OSR simulated by ALOMYSYS.

Tool	Date (days after sowing)	Factor	Plant survival after weeding (plants/plants)		Mature weeds at crop harvest (plants/m ²)		Seed production (seeds/m ²)		Seed bank before seed rain (seeds/m ²)	
Harrow	7	Speed (m/s)								
		2.5	0.70	a	200	a	121633	a	341	a
		3	0.67	b	198	ab	119868	ab	341	a
		3.3	0.64	c	197	b	119336	b	341	a
		Depth (cm)								
		2	0.70	a	200	a	121633	a	337	a
Hoe	56	4	0.58	b	214	a	145339	b	335	a
		Area								
		70%	0.42	a	147	a	44654	a	276	a
		50%	0.59	b	183	b	81135	b	279	b

Except when otherwise indicated, working depth was 2 cm, working speed 2.5 m/s and hoed area was 0.7. Means of a given column and a specific test (speed, depth or area) followed by the same letter are not significantly different at $\alpha = 0.05$ (Analysis of variance with scenario and repetition factors followed by least significant difference test)

Table 7 Long-term evaluation of scenarios with multi-year simulations using ALOMYSYS

Scenario	Short-term infestation (mean over rotation, years 1-3)				Medium-term infestation (mean over rotation, years 13-15)				Long-term dynamics (Spearman correlation coefficient, years 13-26)		
	Mature weeds/m ²		Repetitions where scenario		Mature weeds/m ²		Repetitions where scenario >> reference ²		Correlation (mean) ³	Repetitions where scenario	
	Mean ¹	SE	>> reference ²	<< reference ²	Mean ¹	SE				>> 0 ⁴	<< 0 ⁴
R Herbicide-based reference system	18 c	5			<0.1 a	<0.1			-0.145 ns	0%	10%
M1 Triple hoeing in OSR, sextuple harrowing in cereals	33 f	5	60%	0%	490 d	48	100%		-0.062 ns	10%	10%
M2 Triple hoeing in all crops	42 g	8	60%	0%	568 e	52	100%		-0.059 ns	0%	10%
L1 M1 + 3-year no-till lucerne with optimal cutting (OSR/WW/WB/3L)	27 e	4	10%	10%	36 b	8	0%		-0.131 ns	0%	10%
L2 M1 + 6-year no-till lucerne with optimal cutting (OSR/WW/WB/OSR/WW/WB/6L)	32 f	5	30%	10%	100 c	13	30%		-0.251	0%	20%
L3 L1 with tillage before lucerne	27 e	4	10%	10%	2 a	1	0%		-0.010 ns	30%	20%
P1 L3 with chisel replaced by mouldboard ploughing before each annual crop	13 a	2	0%	20%	0.2 a	0.1	0%		-0.050 ns	20%	20%
P2 L3 with chisel replaced by mouldboard ploughing before OSR only	27 e	4	10%	10%	1 a	1	0%		0.007 ns	10%	0%
P3 L3 with chisel replaced by mouldboard ploughing before WW only	16 b	2	0%	20%	1 a	1	0%		-0.084 ns	0%	0%
P4 L3 with chisel replaced by mouldboard ploughing before WB only	22 d	3	0%	10%	0.4 a	0.2	0%		-0.0002 ns	10%	10%

¹ Means over all repetitions were compared using the linear model $weed\ density_{ijk} = constant + scenario_j + crop_i + repetition_k + error_{ijk}$ with $i \in \{1, 2, 3\}$ (initial infestation) or $\{13, 14, 15\}$ (medium-term infestation) and means followed by the same letter were not significantly different at $\alpha = 0.05$.

² % of repetitions where the infestation of a scenario i was not significantly different based on an analysis with linear model $weed\ density_{ijk} = constant + scenario_j + crop_i + error_{ijk}$ for each repetition $k \in \{1, \dots, 10\}$.

³ Spearman correlation coefficient calculated with PROC CORR of SAS between weed density and year for years 13 to 27.

⁴ % of repetitions where the Spearman correlation coefficient calculated between weed density and year for each repetition for years 13 to 27 was significantly different from zero at $\alpha = 0.05$. ns indicates that this mean correlation is not significantly different from zero at $\alpha = 0.05$.

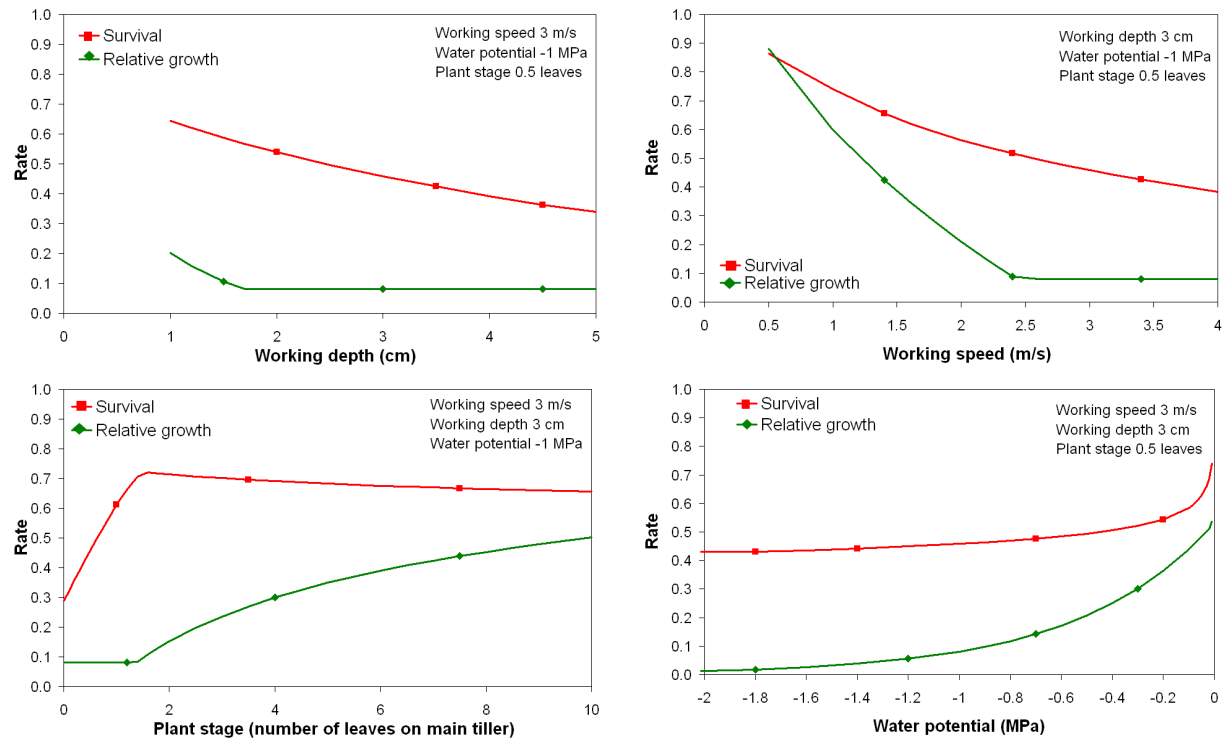


Figure 1. Sensitivity analysis of plant survival and post-harrowing plant growth to harrowing speed and depth as well as soil moisture and blackgrass stage

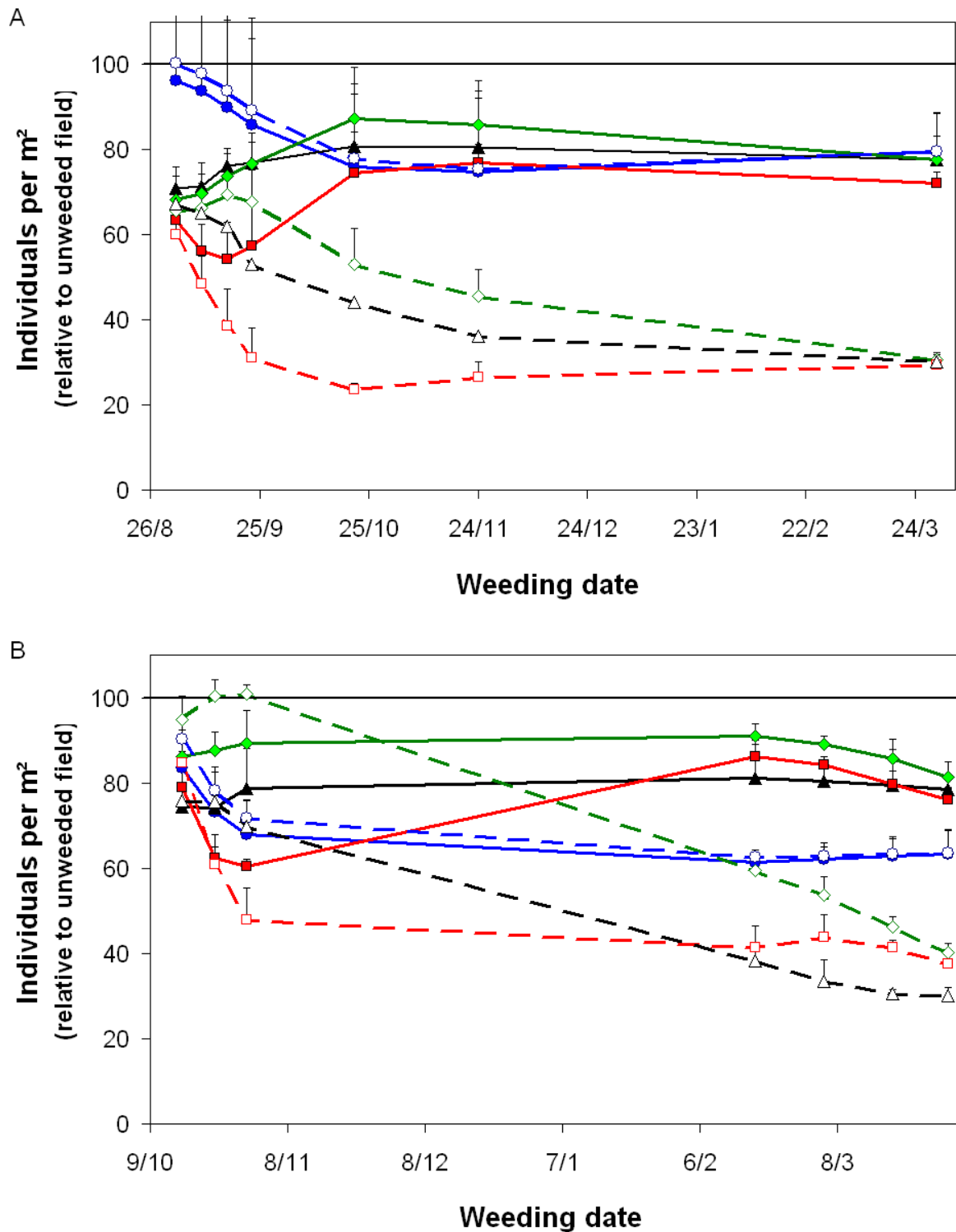


Figure 2. Effect of weeding tool (harrow: continuous line, hoe: broken line) and date on relative variations in blackgrass densities (●: seed bank before seed rain; ▲: plant survival after weeding; ◆: mature plants at harvest; ■: seed production) in oilseed rape (A) and winter wheat (B) simulated with ALOMYSYS (100% = unweeded control). Mean and standard-deviation of ten repetitions simulated with randomly chosen weather scenarios from Dijon (1986-2004). Values above 100 indicate an increase in blackgrass, values below a decrease relative to the unweeded treatment.

Alternative version of Figure 2

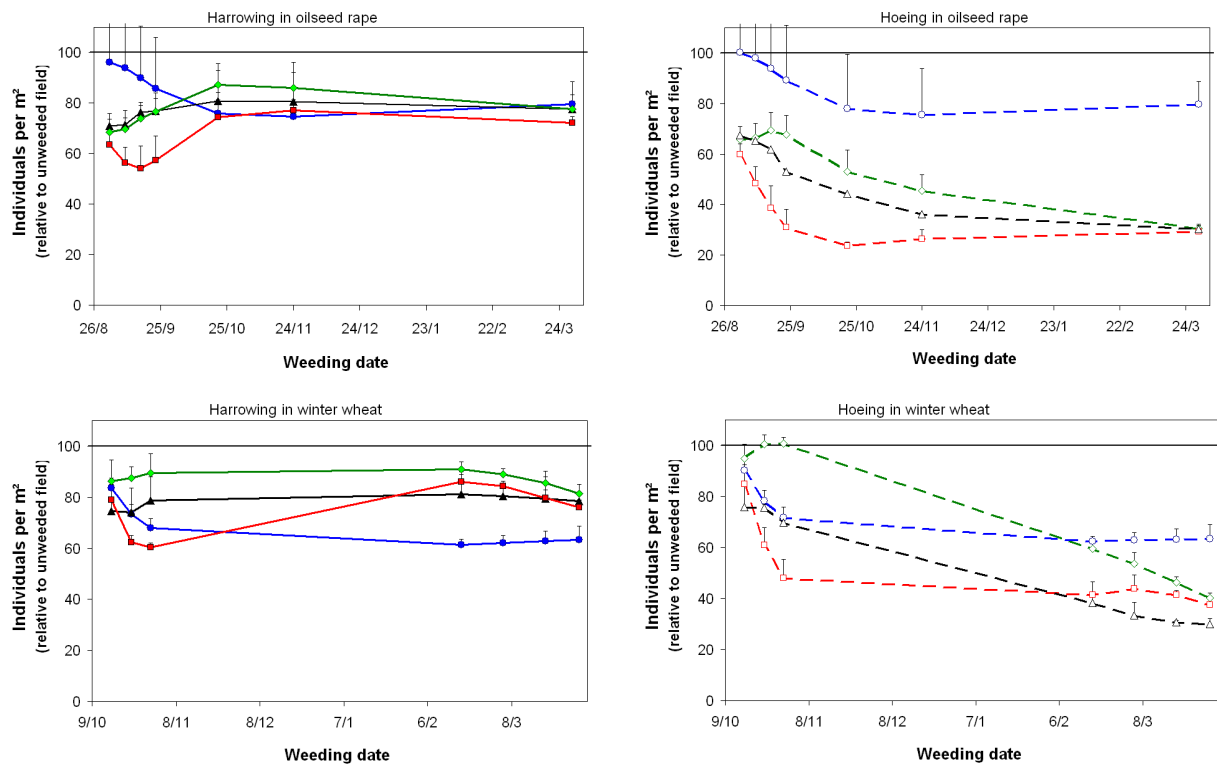


Figure 3. Effect of weeding tool and date on relative variations in blackgrass densities (●: seed bank before seed rain; ▲: plant survival after weeding; ◆: mature plants at harvest; ■: seed production) in two winter crops simulated with ALOMYSYS (100% = unweeded control). Mean and standard-deviation of ten repetitions simulated with randomly chosen weather scenarios from Dijon (1986-2004). Values above 100 indicate an increase in blackgrass, values below a decrease relative to the unweeded treatment.

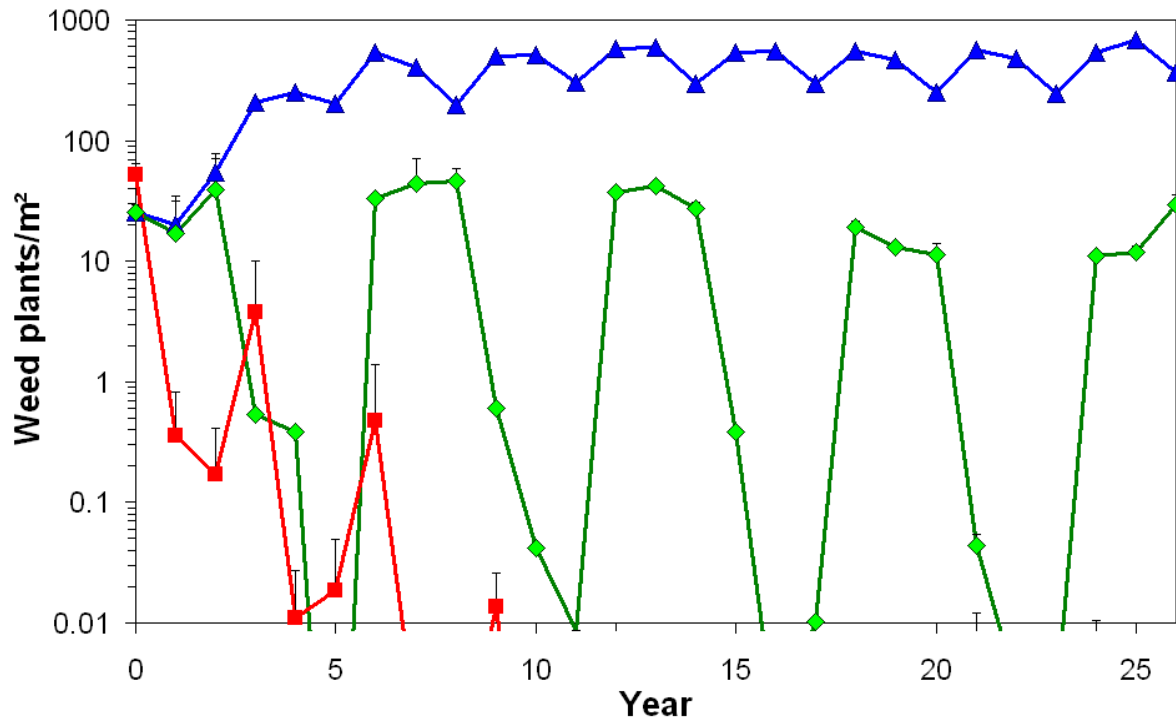


Figure 4. Mature weed densities at crop harvest (mean and standard-error from ten repetitions with randomly chosen weather series) simulated with ALOMYSYS for three scenarios: OSR/WW/WB with herbicides (scenario R, squares), the same rotation with optimal mechanical weeding (scenario M1, triangles) and a six-year rotation with OSR/WW/WB followed by three-year lucerne mown thrice every year (scenario L1, diamonds). The letters on top show the crops (O=oilseed rape, W = winter wheat, B = barley, L = lucerne).