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1 **Assessing non-chemical weeding strategies through mechanistic** 2 **modelling of blackgrass (*Alopecurus myosuroides* Huds.) dynamics**

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21 **Abstract**

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

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

50

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

53 **1. Introduction**

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

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

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

89

90 **2. Material and methods**

91 **2.1. Model structure**

92 **2.1.1. The main features of ALOMYSYS**

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

95 The input variables of ALOMYSYS consist of:

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

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

110 These input variables influence the annual life-cycle of blackgrass (Table 1), in interaction with
111 blackgrass stages (*e.g.* mortality after herbicide application depends on blackgrass stage and density),
112 crop stages (*e.g.* seedling survival after emergence depends on its emergence date relative to the crop
113 emergence date) and environmental conditions (*e.g.* pre-emergent seedling mortality increases with
114 the size and compaction of soil clods as well as soil dryness). All life-stages are described in output
115 files, but the main output variables comprise daily emerging seedlings, total density of mature weeds
116 at crop harvest, their seed production, and the seed bank consisting of viable seeds both on surface and
117 buried at different depths in the soil.

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

120 **2.1.2. The multi-year grassland sub-model**

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

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

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

143 **2.1.3. The mowing sub-model**

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

150

151 **2.1.3.1 Plant mortality**

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

158

159 **2.1.3.2 Flowering and maturity dates**

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

167

168 **2.1.3.3 Tillering and head production**

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

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

176

177 **2.1.3.4 Number of flowers per head**

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

$$186 \quad \text{variation}_{\text{FH}} = 1.62 - 0.000729 \cdot \text{mowing date} + \text{error} \quad r^2 = 0.52 \quad [1]$$

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

190

191 **2.1.3.5 The rate of flowers with a viable seed**

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

$$197 \quad \text{variation}_{\text{SF}} = 1.03 + \text{effect}_{\text{mowing frequency}} + \text{error} \quad r^2 = 0.99 \quad [2]$$

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

200

201 **2.1.4. The mechanical weeding sub-model**

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

209 2000). *L. perenne* was the only grass species studied by Kurstjens *et al.* and its seedlings are likely to
210 respond similarly to *A. myosuroides*.

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

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

218

219 **2.1.4.1 The rate of uprooted plants by harrowing and the leaf area covered by soil**

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

$$\begin{aligned} 231 \log_e(\text{uprooting rate}_{\text{de}}+1) &= 0.0155 - 0.0215 \cdot \log_e(-\text{water potential}) & [3] \\ 232 &+ 0.0853 \cdot \log_e(\text{working speed}) \\ 233 &+ 0.156 \cdot \log_e(\text{working depth}) \\ 234 &- 0.703 \cdot \log_e(\mathbf{LP}_{\text{de}}+1) \end{aligned}$$

$$235 R^2 = 0.73$$

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

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

$$\begin{aligned} 243 \log_e(\text{rate of covered leaf area}_{\text{de}}+1) &= 0.0110 + 0.0184 \cdot \log_e(-\text{water potential}) & [4] \\ 244 &+ 0.356 \cdot \log_e(\text{working speed}) \\ 245 &+ 0.127 \cdot \log_e(\text{working depth}) \end{aligned}$$

246 $-0.162 \cdot \log_e(\mathbf{LP}_{de} + 1)$

247 $r^2 = 0.67$

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

252

253 **2.1.4.2 Survival and growth reduction rates of uprooted and non-uprooted plants**

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

259 For non-uprooted plants: $survival\ rate_{de} = 0.960 - 0.0322 \cdot \log_e(-\text{water potential})$
 260 $- 0.179 \cdot \log_e(\text{working speed})$
 261 $- 0.0449 \cdot \log_e(\mathbf{LP}_{de} + 1)$

262 For uprooted plants: $survival\ rate_{de} = 0.960 - 0.120 \cdot \log_e(-\text{water potential})$ [5]
 263 $- 0.179 \cdot \log_e(\text{working speed})$
 264 $- 0.156 \cdot \log_e(\text{working depth})$
 265 $- 0.396 \cdot \log_e(\mathbf{LP}_{de} + 1)$

266 $R^2 = 0.84$

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

273 For non-uprooted plants: $\log_e(\text{relative weight}_{de}) = 0.103 + 0.0691 \cdot \text{water potential}$
 274 $- 0.0475 \cdot \text{leaf cover rate}_{de}$ [6]

275 For uprooted plants: $\log_e(\text{relative weight}_{de}) = 0.103 + 1.880 \cdot \text{water potential}$
 276 $- 0.737 \cdot \text{leaf cover rate}_{de}$

277 $R^2 = 0.53$

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

282

283 2.1.4.3 Seedling mortality and growth reduction

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

$$\begin{aligned} 287 \text{PM2}_{de} &= \text{PM2}_{d-1e} \\ 288 &\quad \cdot (\text{uprooting rate}_{de} \cdot \text{survival rate}_{de}[\text{uprooted}] \\ 289 &\quad + (1-\text{uprooting rate}_{de}) \cdot \text{survival rate}_{de}[\text{non-uprooted}]) \end{aligned} \quad [7]$$

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

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

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

$$\begin{aligned} 309 m_{de} &= m_{d-1e} \cdot (\text{PM2}_{de}[\text{row}] \cdot 1 \\ 310 &\quad + \text{PM2}_{de}[\text{interrow}] \cdot (\text{uprooting rate}_{de} \cdot \text{relative weight}_{de}[\text{uprooted}] \\ 311 &\quad + (1-\text{uprooting rate}_{de}) \cdot \text{relative weight}_{de}[\text{non-uprooted}]) \end{aligned} \quad [8]$$

312 2.2. Simulations

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

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

322 **2.2.1. The reference system**

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

334 Simulations started with an initial blackgrass emergence of 100 plants/m² during the crop season and
335 lasted for 27 years. Ten repetitions were carried out for each reference system, by randomly choosing
336 each year annual climate scenarios from weather series from 1986 to 2004 recorded at the
337 meteorological station located at the INRA experimental station at Dijon, France (5°2'E, 47°20'N).
338 The associated soil climate variables were estimated with the soil-crop model STICS (Brisson *et al.*,
339 1998b; 2002).

340 **2.2.2. Single mechanical weeding tactics**

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

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

$$353 \log_e(\text{ALOMYSYS output}_{ij}) = \text{constant}$$

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

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

388 27-year-long weather combinations as for the reference simulation. If the alternative scenario was
389 better than the reference (i.e. less infestation than the reference in at least one repetition, never any
390 higher infestation), less stringent weeding options could be tested in the least-risky crops to reduce
391 work and constraints for farmers. Conversely, if the alternative scenario was worse than the reference,
392 additional management options were tested, starting with the most influential cropping system
393 components, i.e. rotation and tillage (Chauvel *et al.*, 2001).

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

$$\begin{aligned} 399 \text{weed density}_{ijk} &= \text{constant} \\ 400 &+ \text{scenario}_i \\ 401 &+ \text{crop}_k \\ 402 &+ \text{error}_{ijk} \end{aligned} \quad [10]$$

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

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

415

416 **3. Results**

417 **3.1. Short-term effects of mechanical weeding**

418 **3.1.1. Single mechanical weeding tactics**

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

422 after crop sowing, harrowing was usually more effective than hoeing, i.e. less plants survived weeding
423 and there were less mature weeds, seed production and surviving seed bank at crop harvest (Table 5).
424 Indeed, harrowing tilled 100% of the field area compared to only 70% for hoeing. Moreover, interrow
425 width had to be increased to allow hoeing, leading to a decrease in WW sowing densities, thus leaving
426 more space for emerging weeds. Plant mortality after hoeing efficiency though increased with the
427 lateness of the operation while the opposite was true for harrowing which did not uproot the larger
428 weeds found later in season (see equation [3]). However, when looking at seed production, harrowing
429 had better to be delayed until 2-3 weeks after sowing (Figure 2). Though the plant mortality rate was
430 slightly lower at that date, more blackgrass seedlings had emerged and were affected by the weeding.
431 Earlier weeding operations occurred before or at the onset of the weed emergence flush and could
432 therefore not destroy the weed seedlings. The seed bank prior to the new seed rain always decreased
433 with weeding date, because the weeding tool tilled the soil and triggered seed germination. In OSR,
434 there was though no effect of early weeding on the seed bank because the soil was still too dry for the
435 weeding tool to stimulate much germination.
436 Despite the inclusion of soil water potential effects in both uprooting and survival equations (see [3]
437 and [5]), plant survival after weeding did not vary significantly between repetitions but mostly
438 depended on weeding date (see partial R^2 in Table 5). The repetition factor, and therefore weather,
439 significantly influenced the other three analysed weed variables, i.e. mature plants at harvest, seed
440 production and seed bank before seed rain. The relevant weather variable here was soil water potential
441 and its effect on seed germination and seedling emergence, thus influencing weed densities and seed
442 production as well as surviving seeds in the soil.
443 Increasing harrowing speed significantly decreased plant survival though the subsequent effect on
444 mature plants and seed production was slight and the effect on seed bank nil (Table 6). Increasing
445 harrowing depth significantly decreased plant survival but mature plants and seed production were
446 increased because of additional seed germination. Decreasing the width of the hoed interrow area and
447 thus the relative hoed field area considerably increased plant survival and mature plants while seed
448 production was almost doubled. The seed bank was also slightly increased because the narrower
449 hoeing triggered less seed germination.

450 **3.1.2. Weeding strategies in oilseed rape**

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

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

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

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

468 **3.1.3. Mechanical weeding in winter wheat**

469 Table 3.B lists the weeding scenarios tested in WW. The general ranking of the scenarios was slightly
470 different to that observed for OSR, with the sextuple harrowing being the best option. The date of the
471 first operation was a very important factor, with scenarios starting weeding three weeks after sowing
472 (30 Oct.) performing best. Double scenarios ranked better than in OSR as in WW, double scenarios
473 finished with a spring weeding, in contrast to double OSR strategies.

474 **3.2. Mowing in tri-annual lucerne**

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

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

487 **3.3. Evaluation of long-term non-chemical weed management**

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

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

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

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

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

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

529 **4. Discussion**

530 **4.1. Modelling approach**

531 The present modelling approach was based on a process-based representation of effects of techniques
532 and their interactions with environmental conditions. These experimental data were preferred to
533 synthetic observations from field trials (e.g. Rasmussen, 1992) because mechanical weeding and, to a
534 lesser degree, mowing have complex and sometimes compensating effects (e.g. seedling mortality vs.
535 triggering of seed germination by tillage) that interact with environmental conditions and weed stages.
536 This approach could be taken because Kurstjens et al. set up detailed experiments to assess the various
537 differential effects (e.g. uprooting, covering plants with soil) in interaction with environment (e.g. soil
538 moisture), weeding characteristics (depth, speed) and weed stages. Similarly, Dalbiès-Dulout and Doré
539 analysed the effect of mowing characteristics on the different stages and yield components of
540 blackgrass. The addition of these various processes to the existing ALOMYSYS model was only
541 possible because of its modular structure and its strong focus on a mechanistic representation of
542 interactions. These characteristics also ease the addition of other weeding implements (e.g. Chicouene,
543 2007) and preventive tactics.

544 However, the disadvantage of this approach is the high number of required condition-specific
545 relationships. This particularly holds for the mechanical weeding submodel. The effect of soil
546 conditions and weed growth stage can only be separated by assessing the height or mass of individual
547 weeds. The necessary data were taken from laboratory experiments because these are the only data on
548 weed survival and growth reduction that are specific for weed size and types of damage as created by
549 implements. Principally, data from artificial physical damaging experiments (Habel, 1954; Jones *et al.*,
550 1995; , 1996; Baerveldt and Ascard, 1999) could have been used as well in this approach, but the
551 representativeness of the artificial damaging is very important though uncertain (Kurstjens and Kropff,
552 2001).

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

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

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

574 **4.2. Preliminary model evaluation**

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

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

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

608 Though these first comparisons to literature reports are encouraging, the submodels added here to
609 ALOMYSYS must be evaluated with independent field data, to determine the conditions in which the
610 model can be safely used, its prediction error as well as deficiencies that must be corrected in future.
611 This evaluation should be conducted at two levels, just as in the simulations carried out here. In the
612 case of mechanical weeding, annual trials should monitor weed survival and reproduction as well as
613 environmental conditions in treatments combining different tools, working depths, soil moisture
614 conditions etc. Multi-year cropping system trials should complete this analysis by looking at weed
615 dynamics over several years, albeit with less detail and frequency. A similar approach was indeed used
616 to evaluate the initial version of ALOMYSYS, looking in detail at weekly emergence in short-term trials
617 (Colbach *et al.*, 2006a) and at multi-year dynamics in long-term cropping systems (Colbach *et al.*,
618 2007).

619 **4.3. Implications for weed management**

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

634 rotation by introducing a perennial legume crop (a frequent strategy in organic farming) was not as
635 efficient as expected. Introducing spring crops preceded by stale seed bank techniques would be much
636 more interesting for managing blackgrass (Chauvel *et al.*, 2001; Colbach *et al.*, 2007; Chauvel *et al.*,
637 2009).

638 The simulated efficiency of mechanical weeding control and other weed-relevant cultivation
639 techniques could probably be improved if crop management was not considered as a fixed programme
640 where operations are always carried out at the same date, irrespective of weather or soil conditions.
641 Indeed, the present simulations showed that weather conditions have a large impact on weed control
642 effectiveness. If the simulated operation timing depended on prevailing weather conditions, mimicking
643 the decision making of farmers waiting for the good conditions to implement the mechanical weeding,
644 weeding efficiency would increase and vary less between years. If decision-rule models (Bergez *et al.*,
645 2002; Keating *et al.*, 2003; Chatelin *et al.*, 2005) could be connected to ALOMYSYS to take account of
646 practical guidelines (depending on weather, soil moisture and crop and weed growth stage) and
647 trafficability restrictions. Simulations would thus be more robust and used to improve guidelines, to
648 assess risks and associated costs (crop damage, hand weeding, future control demands).

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

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

666
667

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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 n
Hoe 30 Oct.	Hoe 1 March	Hoe 1 April	22838	v u
Hoe 30 Oct.	Harrow 1 March	Hoe 1 April	24978	u
Harrow 30 Oct.	Hoe 1 March	Hoe 1 April	29504	u t
Hoe 30 Oct.	Hoe 1 March	Hoe 1 April	29885	u t
Hoe 30 Oct.	Hoe 1 March		30794	s u t
Harrow 30 Oct.	Harrow 1 March	Hoe 1 April	31228	s u t
Harrow 30 Oct.	Hoe 1 March	Harrow 1 April	39043	s r t
Harrow 30 Oct.	Hoe 1 April		40708	s r
Harrow 30 Oct.	Hoe 20 Nov.		43857	r q
Harrow 30 Oct.	Hoe 1 March		45962	p r q
Harrow 30 Oct.	Hoe 19 Feb.		46470	p r q
Harrow 23 Oct.	Hoe 20 Nov.		46984	p r q
Harrow 30 Oct.	Harrow 30 Nov.	Harrow 1 April	53826	p o q
Hoe 30 Oct.	Harrow 1 March	Harrow 1 April	56033	p o n
Harrow 30 Oct.	Harrow 1 March	Harrow 1 April	63617	m o n
Hoe 1 April			65633	m n
Harrow 23 Oct.	Harrow 20 Nov.		65838	m l n
Harrow 30 Oct.	Harrow 20 Nov.		70974	K m l
Hoe 20 March			73820	K m j l
Hoe 19 Feb.			75942	K j l i
Hoe 5 March			77546	K h j i
Harrow 30 Oct.	Harrow 1 April		80233	K h j g i
Harrow 19 Feb.	Harrow 10 March	Harrow 1 April	81576	h j g i
Harrow 30 Oct.	Harrow 1 March		84842	h g i
Harrow 30 Oct.	Harrow 19 Feb.		87518	h g
Hoe 30 Oct.			88707	g
Harrow 23 Oct.			106557	f
Harrow 30 Oct.			107033	f
Hoe 23 Oct.			110901	f
Harrow 1 April			133225	e
Harrow 20 March			138801	e
Harrow 16 Oct.			143144	d e
Harrow 5 March			149216	d c
Harrow 19 Feb.			153328	d c
Hoe 16 Oct.			153765	c
Control			177374	b
Hoe 30 Oct.	Harrow 1 April		210222	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).

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				Repetition	R ²
		Weeding tool		Weeding date			
		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>	<i>0.12</i>		<i>0.78</i>		<i>0.00</i>	<i>0.90</i>
Mature weeds at crop harvest (plants/m ²)	Regression coefficient	0.33	-0.33	-0.23	0.054	nl	
	<i>Partial R²</i>	<i>0.09</i>		<i>0.29</i>		<i>0.53</i>	<i>0.91</i>
Seed production (seeds/m ²)	Regression coefficient	0.27	-0.27	-0.25	0.066	nl	
	<i>Partial R²</i>	<i>0.025</i>		<i>0.17</i>		<i>0.71</i>	<i>0.90</i>
Seed bank before seed rain (seeds/m ²)	Regression coefficient	0.013	-0.013	-0.90		nl	
	<i>Partial R²</i>	<i>0.003</i>		<i>0.14</i>		<i>0.79</i>	<i>0.93</i>

B. Winter wheat

Weed stage		Factor				Repetition	R ²
		Weeding tool		Weeding date			
		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>	<i>0.18</i>		<i>0.74</i>		<i>0.00</i>	<i>0.92</i>
Mature weeds at crop harvest (plants/m ²)	Regression coefficient	0.37	-0.37	-0.26	ns	nl	
	<i>Partial R²</i>	<i>0.10</i>		<i>0.43</i>		<i>0.38</i>	<i>0.91</i>
Seed production (seeds/m ²)	Regression coefficient	0.32	-0.32	-0.20	0.060	nl	
	<i>Partial R²</i>	<i>0.09</i>		<i>0.34</i>		<i>0.43</i>	<i>0.87</i>
Seed bank before seed rain (seeds/m ²)	Regression coefficient	0.060	-0.060	-0.092	-0.070	nl	
	<i>Partial R²</i>	<i>0.003</i>		<i>0.11</i>		<i>0.87</i>	<i>0.97</i>

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
	4	0.58	b	214	a	145339	b	335	a	
Hoe	56	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.

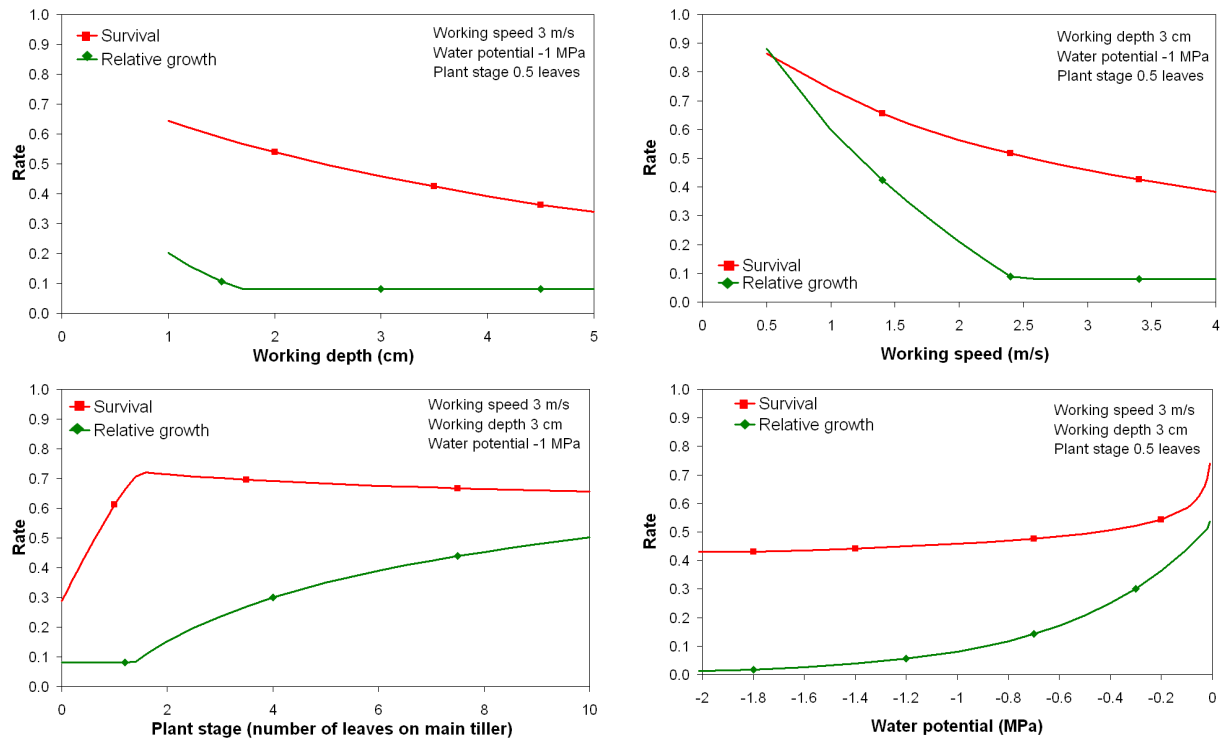


Figure 1. Sensitivity analysis of plant survival and post-harrowing plant growth to harrowing speed and depth as well as soil moisture and blackgrass stage

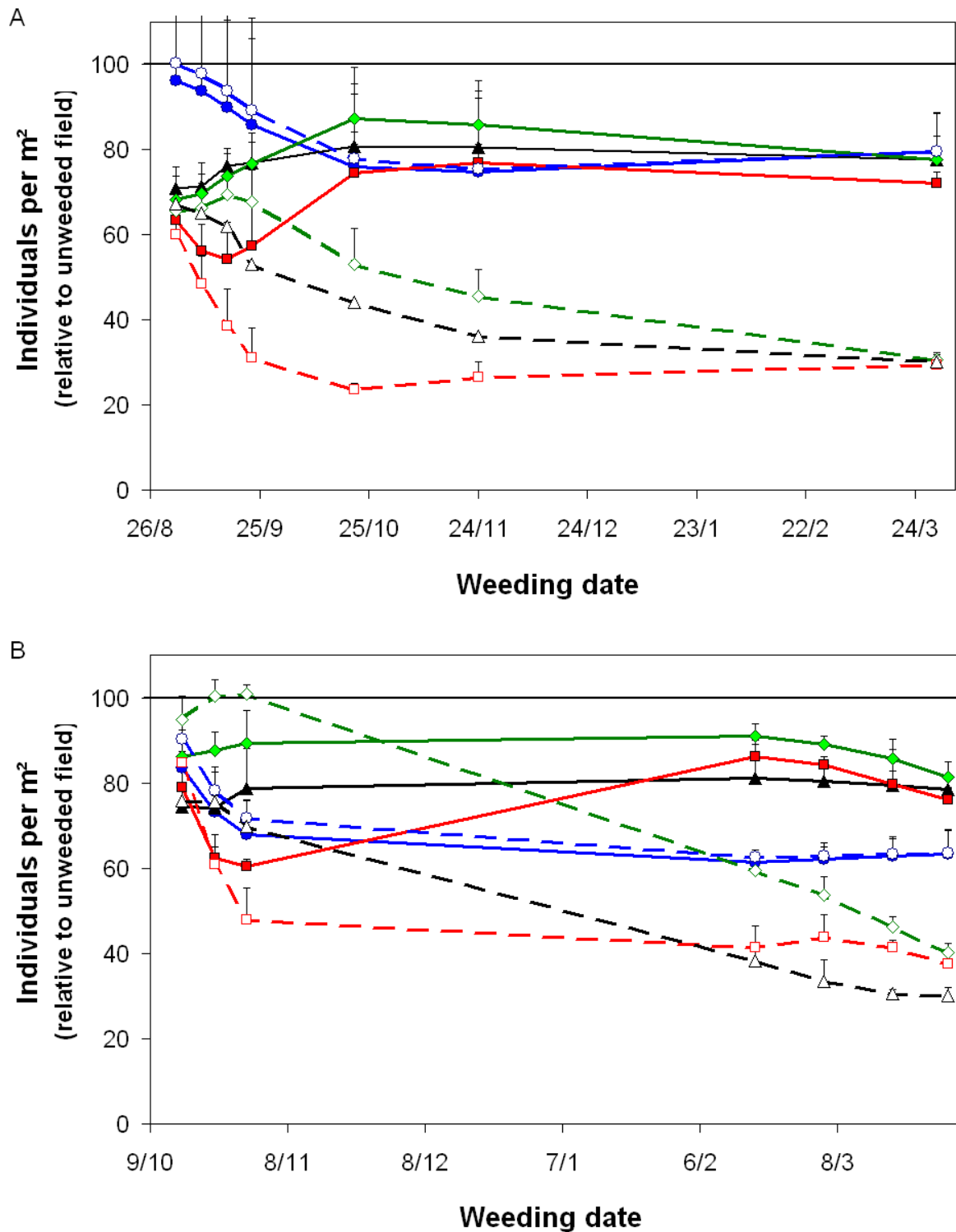


Figure 2. Effect of weeding tool (harrow: continuous line, hoe: broken line) and date on relative variations in blackgrass densities (●: seed bank before seed rain; ▲: plant survival after weeding; ◆: mature plants at harvest; ■: seed production) in oilseed rape (A) and winter wheat (B) simulated with 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

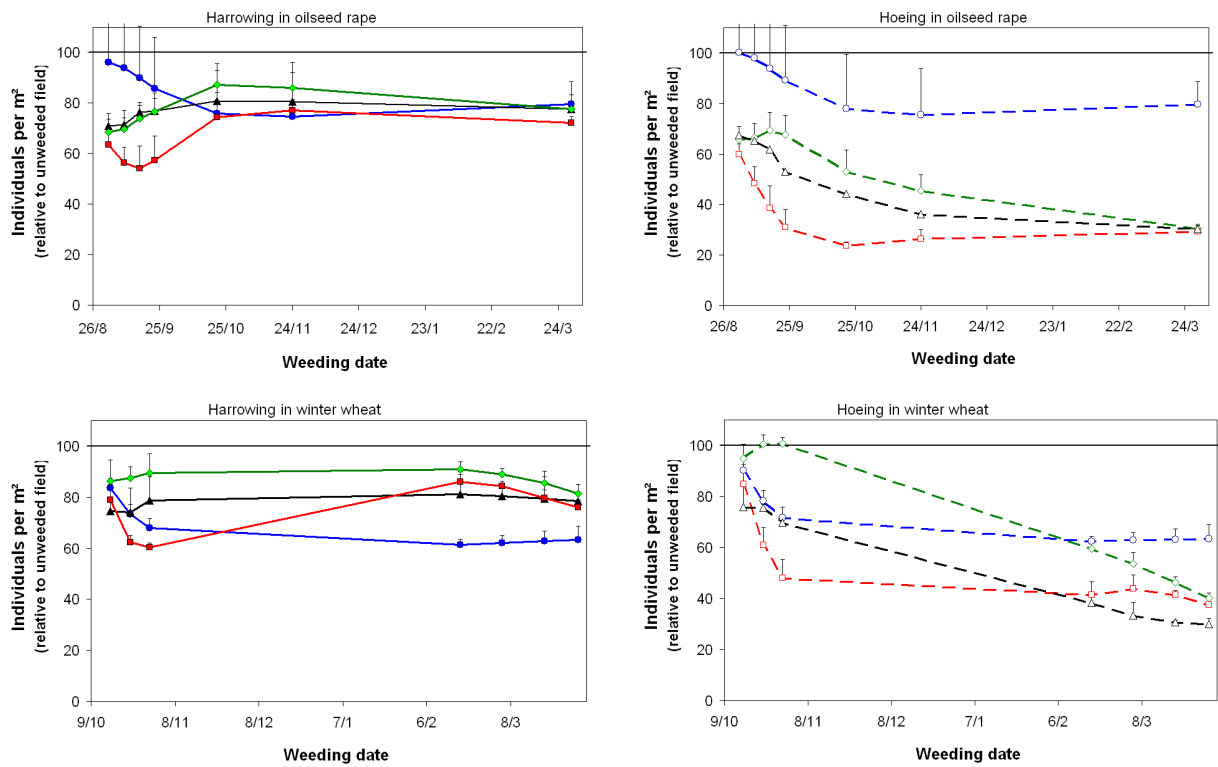


Figure 3. Effect of weeding tool and date on relative variations in blackgrass densities (●: seed bank before seed rain; ▲: plant survival after weeding; ◆: mature plants at harvest; ■: seed production) in two winter crops simulated with ALOMYSYS (100% = unweeded control). Mean and standard-deviation 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.

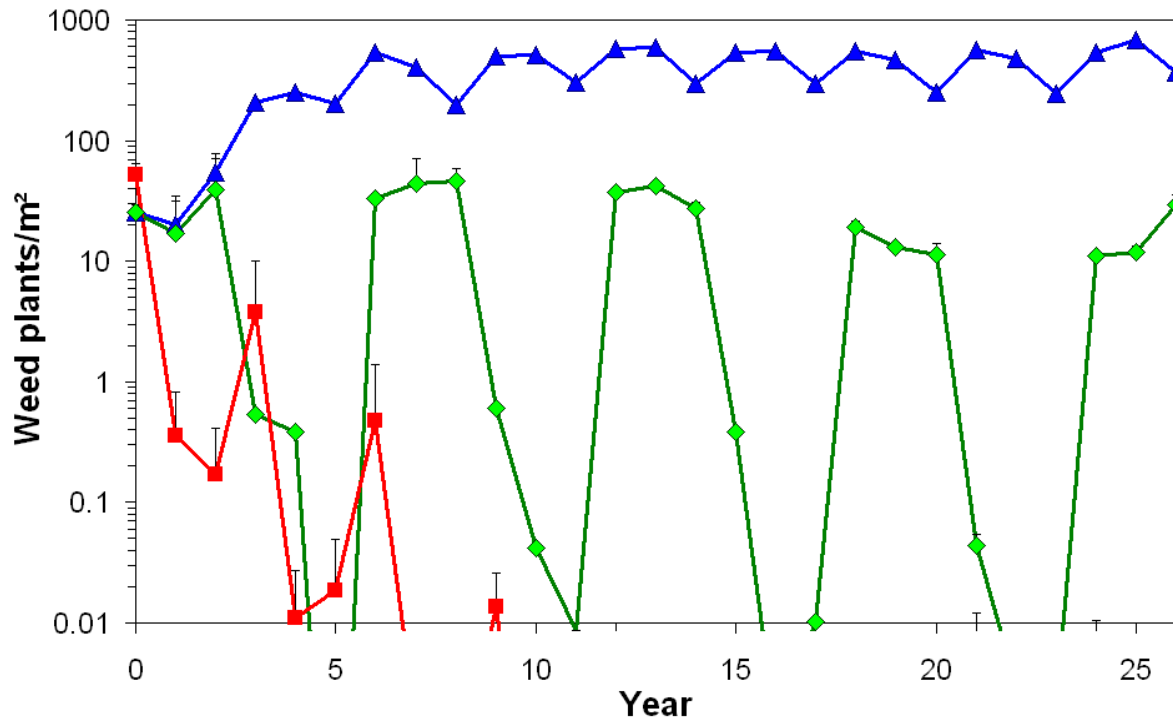


Figure 4. Mature weed densities at crop harvest (mean and standard-error from ten repetitions with randomly chosen weather series) simulated with ALOMYSYS for three scenarios: OSR/WW/WB with herbicides (scenario R, squares), the same rotation with optimal mechanical weeding (scenario M1, triangles) and 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).