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Effectiveness of field isolation distance, tillage practice, cultivar type and crop rotations in controlling phoma stem canker on oilseed rape

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Abstract

Modern agriculture has led to simpler agricultural landscapes that favour the spread of pathogens and increase pressure from pests and diseases. Landscape-dependent interactions between crops and pathogens, including disease related dispersal patterns, and the benefits of reducing pathogen significance call for the design of disease-suppressive landscapes. Model-based assessment is the most efficient method of choosing among management strategies. Based on a case study in France, we ranked the effectiveness of different crop mosaics for control of phoma stem canker on winter oilseed rape (WOSR). Assessed crop mosaics were developed from strategies defined by local stakeholders: (1) isolating target from source fields (all WOSR or only WOSR harbouring RlmX specific resistance), and (2) specifying tillage on WOSR stubble according to cultivar type (with or without RlmX). Model simulations highlighted the effectiveness of WOSR-isolation as compared to RlmX-isolation. Our analyses suggest that tillage (mouldboard ploughing) was the most important factor in

explaining the size and genetic structure of the pathogen population (determinant in explaining the breakdown of resistance), and yield loss. While the pathogen population and yield loss decreased with intensive management of non-RlmX-cultivars (85% of WOSR), the same management with RlmX-cultivars modified the genetic structure of the pathogen population. Increasing isolation distances led to reductions in pathogen population and yield loss only in the strategy of WOSR-isolation. Isolating source and target RlmX-cultivar had no effect on the evolution of the population's genetic structure. Although effective in phoma stem canker control, changing tillage can require significant changes for farms. Isolation distance would require extensive information on the landscape, and imply an aggregation of crops that might or might not be possible depending on a farm's spatial organization. This study could lead to the design of a Decision Support System targeting high risk (diseased) WOSR fields to be ploughed or isolated from the following year's cultivation.

Keywords: yield loss, cultivar resistance, pathogen population, strategy ranking, spatially-explicit model, mosaic design

Highlights

- Stakeholders designed tillage and isolation rules to design pest-suppressive crop mosaics.
- Mosaics were assessed on three complementary criteria with a spatially-explicit model.
- Intensive management of WOSR stubble was the most efficient factor.
- Isolation distances were efficient in decreasing yield loss and pathogen population.
- Implementing efficient strategy would require both individual and collective actions.

1 1. Introduction

2 In recent decades, modern agriculture has led to the simplification of agricultural landscapes,
3 both in terms of structure and crop composition (Stoate *et al.*, 2001; Baessler and Klotz,
4 2006). This intensification process, linked with a simplification of cropping systems (Stoate *et*
5 *al.*, 2001), has strongly reduced crop genetic diversity in the field, thus favouring pathogen
6 spread (Stuckenbrock and McDonald, 2008), and driving agrosystems towards increased
7 vulnerability to pests and diseases (Meehan *et al.*, 2011). With significant yield losses from
8 pests and diseases (Oerke and Dehne, 2004; Oerke, 2006), crop arrangements in time and
9 space (i.e., crop mosaics) represent a critical parameter to mitigate susceptibility to these
10 losses. For instance, landscape composition and complexity have been identified as driving
11 parameters of the rate of pollen beetle parasitism (Rusch *et al.*, 2011), aphids and wheat
12 diseases (Gosme *et al.*, 2012), and the pathogen population structure responsible for wheat
13 leaf rust (Papaix *et al.*, 2011). These types of landscape-dependent crop-pathogen interactions
14 and the desire to reduce pathogen significance call for the design of disease-buffering or
15 disease-suppressive landscapes (Skelsey *et al.*, 2010).

16 For pathogens exhibiting a dispersal process (either active, e.g., insects, or passive, e.g., wind-
17 or water-dispersed), pest-suppressive landscapes have to be designed both in terms of
18 composition (e.g., proportion of the different crops/cultivars; Papaix *et al.*, 2011), and
19 configuration, including the exact and relative locations of crops and associated cropping
20 systems (Leenhardt *et al.*, 2010). In addition, landscape temporal evolution has to be
21 characterized as crop-pathogen interaction exhibiting a year-to-year relationship (e.g., for
22 pollen beetle in Rusch *et al.*, 2011; for phoma stem canker in Bousset *et al.*, 2015). The
23 consideration of spatial and temporal scales depends on processes and knowledge about the
24 specific topic to address (e.g., crop-pathogen interactions), leading to rules defined in time
25 (crop rotations and crop return time; Castellazzi *et al.* 2010), and/or in space (isolation

26 distance or buffering zones) (e.g., Skelsey *et al.*, 2010 on potato late blight; Colbach *et al.*,
27 2009 on maize gene flow).

28 Although disease-suppressive landscapes can theoretically be identified, their design and
29 assessment remain challenging. Their design should begin by the identification of potentially
30 efficient control methods (cultural, physical, biological or chemical), and their effect on
31 pathogen populations, which have to be defined both in time and in space (Aubertot *et al.*,
32 2006). Once identified, strategies that organize and coordinate these control methods on a
33 landscape scale have to be built. Involving stakeholders in this step can help to develop and
34 explore more suitable proposals (Brandenbourg *et al.*, 1995), especially for agricultural
35 landscapes where the choice and location of cropping systems are decided by local farmers
36 (Primdahl, 1999), and influenced by local stakeholders (e.g., input providers, crop collector).
37 Such involvement helps the integration of local specificities, providing more complete
38 information on characteristics such as soil, climate, and markets (Reed, 2008; Voinov and
39 Bousquet, 2008). Experimentation to assess the designed landscapes can be problematic,
40 especially when exploring the effectiveness of several possible pre-identified alternatives, i.e.
41 various arrangements of crops and control methods (Skelsey *et al.*, 2010). Explorative
42 modelling of the landscape system appears to be a suitable, and even necessary option. This
43 method uses dynamic and spatially explicit models representing the necessary processes at
44 field and landscape scales (e.g., Veldkamp *et al.*, 2001; Lô-Pelzer *et al.*, 2010b).

45 Phoma stem canker of oilseed rape (causal agent *Leptosphaeria maculans* fungus) is
46 responsible for major yield and economic loss worldwide (Fitt *et al.*, 2006) and is
47 characterized by crop-pathogen interactions, and potential control methods, which are defined
48 in time and space (Aubertot *et al.*, 2006; Lô-Pelzer *et al.*, 2010b). Its epidemic cycle exhibits
49 a year-to-year recurrence, and the primary inoculum (spores) is produced on winter oilseed
50 rape (WOSR) stubble. These spores are wind-dispersed up to 5-8 kilometres (Bokor *et al.*,

51 1975), and can subsequently fall and infect young oilseed rape (Hall, 1992). A distance of
52 500 m between fields has been highlighted as theoretically efficient to avoid epidemics
53 (Marcroft *et al.*, 2004). At field level, the main control method is the use of resistant cultivars.
54 Two types of resistance can be used: quantitative (partial) resistance, controlling the extent of
55 the disease (Delourme *et al.*, 2006), or qualitative (specific) resistance (RlmX-gene), which
56 prevents the disease if a common resistance gene is harboured by both the landing pathogen
57 and the cropped WOSR cultivar (Plissonneau *et al.*, 2016). However, large-scale cultivation
58 with a qualitatively-resistant cultivar can quickly lead to the breakdown of its specific
59 resistance (Rouxel *et al.*, 2003), and require other associated control methods. Field control
60 methods include WOSR sowing date, fertilization (Aubertot *et al.*, 2004), tillage for WOSR
61 stubble management (Schneider *et al.*, 2006), and fungicide applications that are only
62 effective during a limited time span (Gladders *et al.*, 2006). These methods can help control
63 the disease by two means: reducing the size of the pathogen population, and limiting the
64 selection pressure on pathogen populations (Aubertot *et al.*, 2006). To be efficient, these
65 control methods have to be combined and organized in space and time through ‘integrated’
66 strategies that combine agronomic practices and/or the deployment of cultivar genotypes (e.g.,
67 minimum between-field distance) (Gladders *et al.*, 2006; Sprague *et al.*, 2006).
68 Integrating results (i.e., processes, scales) of empirical studies in a modelling framework can
69 help to understand and tackle the many interactions between crop and pathogen and their
70 spatio-temporal dynamics (e.g., on potato late blight in Skelsey *et al.*, 2009, 2010). Indeed,
71 such strategies cannot be tested in the real world because of their necessarily large spatio-
72 temporal scales (Legg, 2004). Spatially explicit modelling is thus seen as very useful to assess
73 performances of strategies designed at large spatial and temporal scales (Hijmans and van
74 Ittersum, 1996; Vinatier *et al.*, 2016). Such models can then be used as virtual laboratories
75 (Charnell, 2008) to conduct *ex ante* simulation experiments (i.e. strategy testing) at large

76 scales. Using this type of models in combination with expert knowledge can improve the
77 realism of such simulation experiments (e.g., Sadok *et al.*, 2009).

78 For phoma stem canker of oilseed rape, SIPPOM-WOSR is, up to our knowledge, the only
79 spatially explicit model taking into account the effects on disease development, in time and
80 space, of the whole set of cropping practices impacting disease control, i.e., proportion and
81 location of oilseed rape, cultivar type, sowing date and rate, fertilization and tillage practices,
82 and fungicide application (Lô-Pelzer *et al.*, 2010a, 2010b). This model was applied on
83 “extreme situations”, by testing the effect on pathogen population size of two contrasted crop
84 management plans (limited vs. good disease control) and two virtual landscapes (random
85 location of spores’ sources/targets vs. maximizing the distance between sources and targets)
86 (Lô-Pelzer *et al.*, 2010b). These simulations confirmed the general effect of crop management
87 (tillage practices, sowing date and density) and source/field distances on *Leptosphaeria*
88 *maculans* pathogen population (Lô-Pelzer *et al.*, 2010b). As the implementation of integrated
89 pest control strategies requires the participation of stakeholders (Rusch *et al.*, 2010),
90 SIPPOM-WOSR was then used in a participatory scenario approach, where local stakeholders
91 numerically designed future cropping systems that could happen in case of contextual changes
92 (Hossard *et al.*, 2013). These cropping systems were simulated with SIPPOM-WOSR to
93 assess their effect on phoma stem canker control, with regards to indicators describing the
94 pathogen population (size, genetic structure) and subsequent yield loss. Simulations were
95 analysed in order to (1) identify efficient scenarios (Hossard *et al.*, 2015b), (2) highlight, rank
96 and quantify the effect of the most impacting cropping practices (Hossard *et al.*, 2013, 2015a,
97 2015b), and (3) identify the spatial scale at which cropping practices influence the pathogen
98 genetic structure (Hossard *et al.*, 2015a). However, the simulations performed in these studies
99 mostly corresponded to model ‘testing’ by the stakeholders, and led to a kind of “sensitivity
100 analysis” on cropping practices, more than to the design coherent strategies. Indeed, the

101 designed scenarios included extreme values for key variables (e.g., crop rotation, cultivar
102 characteristics, random crop allocation) leading to a low chance that such scenarios would
103 happen in reality (Hossard *et al.*, 2013, Hossard *et al.*, 2015b), and thus provided a limited
104 support for local stakeholders. Nevertheless, such models are of interest for local stakeholders
105 as they can assess the effects of coordinated actions aiming at solving a local issue (Souchère
106 *et al.*, 2010). Following the previous studies on the most sensitive model variables,
107 parameters and inputs (Lô-Pelzer *et al.*, 2010a; Hossard *et al.*, 2015a, 2015b), SIPPOM-
108 WOSR could then help local stakeholders to foresee the consequences on phoma control of
109 different coherent strategies of cropping systems and their spatial distribution, contributing to
110 support their strategic thinking by an *ex ante* assessment of multi-plot and multi-years
111 strategies.

112 Based on a real-world case study located in France, this paper is aimed at characterizing,
113 comparing, and ranking the effectiveness of different types of crop mosaics for phoma stem
114 canker control. The designed crop mosaics were built from different cropping strategies,
115 defined by local stakeholders: (1) isolating target fields from source fields in time and/or
116 space, and (2) specifying tillage practices according to their cultivar type. These mosaics,
117 describing both annual cropping plans and cropping systems, were assessed with SIPPOM-
118 WOSR (Lô-Pelzer *et al.*, 2010a, 2010b).

119

120 2. Material and methods

121 2.1. Method overview

122 The design, assessment, and comparison of strategies combining cropping practices and their
123 allocation for efficient phoma stem canker control were performed in four steps that combine
124 a participatory approach and numerical simulations with a spatially-explicit model (Figure 1):

125 A. Stakeholders designed strategies to control phoma stem canker in their region. These
126 strategies consisted of rules for combining and allocating crops and cropping practices to
127 fields. Two main strategies were designed: isolation of crops or specific cultivars, and setting
128 of specific tillage practices (to manage WOSR stubble) according to cultivar types.

129 B. In the second step, these rules were implemented to build mosaics of crops and cropping
130 practices at the landscape scale. Based on a map of the studied region (Figure 2), between-
131 fields distances were calculated to assign WOSR, specific cultivars and tillage practices
132 annually to each field for each strategy.

133 C. In the third step, these mosaics were simulated with the spatially-explicit model SIPPOM-
134 WOSR (Lô-Pelzer *et al.*, 2010a, 2010b) to assess their impacts on phoma stem canker.

135 D. In the fourth step, statistical analyses were performed to assess and rank the strategies
136 according to their effectiveness for phoma stem canker control, i.e., the ability of strategies to
137 control phoma epidemics and preserve resistance. Strategies were compared with three
138 complementary criteria (size and genetic structure of the pathogen population, and yield loss
139 due to phoma).

140

141 # Figure 1 approximately here #

142

143 2.2. Study area

144 Our case study was located in the Picardie region (NUTS-2), in northern France. In this
145 region, an agricultural context (Oise NUTS-3) was defined as corresponding to specific soil
146 characteristics and cropping systems. Local stakeholders defined cropping systems (Hossard
147 *et al.*, 2015b) characterized by a 7-year crop rotation (with one WOSR every 7 years, i.e.
148 14.3% of WOSR each year). WOSR is sown at the end of august, at a mean density of 45
149 seeds m⁻², with 15% of sown WOSR being RlmX-cultivars. Stakeholders associated RlmX-

150 cultivars (qualitatively resistant) with a low level of quantitative resistance, while in our case
151 study, non-RlmX-cultivars were associated with a high level of quantitative resistance.

152 Summer organic fertilization (before sowing) is applied on about 20% of WOSR, and half of
153 annual WOSR acreages are sprayed with triazole fungicide. In the reference case, WOSR
154 stubble is managed with one passage of stubble breakers (SB) for 33% of the WOSR fields,
155 and two passages for 67% of the fields.

156 The field map used for model simulations corresponded to an area close to Beauvais
157 (coordinates: 49°25'54.8''-49°28'51.2''N; 02°09'13.0''-02°15'13.8''E). This map was
158 composed of 158 fields and incorporating an area of 16.7 km² (Figure 2). We used weather
159 data from *Meteo France*, corresponding to a weather station close to Beauvais
160 (49°26'42''N-02°07'36''E). This area shows a small town in its central part, and small
161 woody areas mostly in its southern part (Figure 2), which are considered as flat uncultivated
162 areas (i.e. not acting as barriers for spores' dispersal).

163

164 # Figure 2 approximately here #

165

166 2.3. Design of cropping mosaics

167 Following the method of Hossard *et al.* (2013), local stakeholders designed strategies
168 combining isolation of pathogen source fields and tillage options for WOSR stubble
169 management (Table 1).

170

171 2.3.1. Isolation rules

172 Field isolation was defined in time, with WOSR fields of year y+1 (receptor/target fields)
173 being spatially isolated from WOSR fields of the preceding year y (source fields) due to the
174 disease epidemiology involving the dissemination of the spores from infected stubble (WOSR

175 of year y) (Hall, 1992). The isolation of target fields therefore means not sowing either
176 WOSR or RlmX-cultivars in the neighbourhood of source fields (Figure 2). Two different
177 types of fields were considered for isolation: all winter oilseed rape crops (whatever their
178 cultivar type) or only one specific cultivar type (cultivars with the RlmX-gene). Stakeholders
179 defined three isolation distances: adjacent fields (0 m), and buffer zones of 500 m or 1,000 m
180 around source fields.

181 For each isolation distance and isolation target (WOSR or RlmX-cultivars), stakeholders
182 wanted to explore two frequencies of WOSR or RlmX-cultivars in the landscape: (1) the
183 reference of 14.3% (corresponding to 7-year rotation), and (2) a higher frequency of 20%
184 (corresponding to a 5-year rotation). The rule was thus to grow WOSR on each field every 5
185 or 7 years. For the WOSR isolation strategy, the annual frequency of RlmX-cultivars
186 corresponded to a reference of 15% of WOSR that was provided by local stakeholders. For
187 RlmX isolation strategy, the stakeholders defined two options characterizing the temporal
188 synchrony of RlmX-cultivars. The first option was to keep a constant frequency across time
189 (15%, as for WOSR isolation strategy). The second option was to set a temporal asynchrony
190 for RlmX-cultivar resulting in a frequency of RlmX-cultivar three times higher in year y than
191 in year $y+1$. For this option, the multi-year frequency was kept to the reference (15%), so
192 annual RlmX frequency was 25% for year y and about 8.33% ($25/3$) for year $y+1$.

193

194 2.3.2. Cultivar-specific stubble management

195 In combination with the isolation rules, stakeholders designed strategies of WOSR stubble
196 management. Three options of tillage were designed: mouldboard ploughing (MB), two
197 passages of stubble breaking (SB), or the reference (1/3 of the fields with one SB passage and
198 2/3 with two SB passages). Tillage options were applied either on all WOSR stubble or
199 separately for cultivar types (with and without RlmX-gene). This led to nine stubble

200 management combinations (3 options for RlmX-cultivars, and 3 options for the cultivars
201 without the RlmX gene).

202

203 2.3.3. Implementation rules

204 Distances between fields were calculated with the R package ‘rgeos’ (Bivand and Rundel,
205 2016). Ten thousand multi-year crop mosaics were realized for each of the twelve
206 combinations of the three criteria: isolation distance (0 m, 500 m, or 1,000 m), isolation target
207 (WOSR or RlmX-cultivars), and WOSR frequency (14.3% or 20%). For each mosaic, the 1st
208 year crop allocation to fields was random, and isolation rules were applied for the following
209 years. For each year, the WOSR acreage objective was constant. For the mosaics with 0 m
210 isolation distance (adjacent fields), the fields selected for WOSR cropping in year y-1 had to
211 be non-adjacent, and at a distance lower than 500 m of WOSR of year y. Similarly, field
212 selection for the 500 m isolation distance incorporated WOSR fields located between 500 m
213 and 1,000 m from the source fields. For each factor combination, three crop mosaics were
214 chosen for simulation with the spatially-explicit model SIPPOM-WOSR. These three
215 replicates were chosen in order to minimize the acreages of fields where no rapeseed could be
216 grown during the 5 or 7 years. Tillage (residue management) was then assigned to WOSR
217 fields according to the 9 options, with a random allocation of one or two passages of stubble
218 breakers for the reference tillage option in WOSR fields.

219 Isolation rules for WOSR fields, combined with tillage options, led to 162 mosaics (3
220 replicates x 9 tillage options x 3 isolation distances x 2 WOSR frequencies; Table 1). Isolation
221 rules for RlmX-cultivar fields, combined with tillage options, led to 324 simulated mosaics (3
222 replicates x 9 tillage options x 3 isolation distances x 2 WOSR frequencies x 2 temporal
223 options –synchronous/asynchronous; Table 1).

224

225 # Table 1 approximately here #

226

227 2.4. Model-based simulation of the strategies

228 SIPPOM-WOSR simulates the effects of cropping practices and their spatial locations on the

229 evolution of phoma stem canker disease (Lô-Pelzer *et al.*, 2010b). The model uses daily

230 weather data and spatially distributed information on field soils, pathogen population, and

231 cropping system characteristics. Cropping system information is thus provided at the field

232 scale, with details on winter oilseed rape frequency and management (cultivar, sowing date

233 and rate, autumnal fertilization, fungicide application and tillage on stubble after WOSR

234 harvest). SIPPOM-WOSR combines population, epidemiological and crop modelling

235 approaches through five sub-models: (i) the production of primary inoculum in source fields,

236 (ii) the dispersal of ascospores produced in source fields, (iii) the genetic compatibility

237 between ascospores dispersed from source to target fields, (iv) the growth of winter oilseed

238 rape, and (v) the infection of WOSR by the pathogen and associated yield loss. Using

239 process-based equations, SIPPOM-WOSR simulates three indicators of phoma stem canker

240 management: two epidemiological indicators (size and genetic structure of the pathogen

241 population) and one agro-economical indicator (yield loss due to phoma disease). Model

242 functioning, equations and parameters are detailed in Lô-Pelzer *et al.* (2010a, 2010b).

243 Each mosaic was run with the model SIPPOM-WOSR for a five-year simulation (one year for

244 model initialization and four years of simulations; as performed in Hossard *et al.*, 2013;

245 2015a; 2015b), with initial model parameters (see details in Lô-Pelzer *et al.*, 2010a; 2010b).

246

247 2.5. Analyses of strategy performance

248 Mosaics were evaluated with three criteria: the size of the pathogen population (number of

249 spores), the fraction of virulent pathotypes on RlmX-gene (hereafter called avrlmX, in %),

250 and the yield loss due to phoma epidemics (% of potential yield). For each simulated mosaic,
251 these criteria were averaged over the simulation years, at the landscape scale, in terms of
252 annual area-weighted values (annual area-weighted sum for population size and annual area-
253 weighted average for yield loss and avrlmX).

254 Two complementary analyses were performed to assess the effectiveness of isolation
255 strategies for phoma management. We first developed linear models to test the effect of the
256 different factors on the three evaluation criteria for each of the two isolation strategies
257 (WOSR or RlmX). The included explanatory factors were WOSR frequency, isolation
258 distances, tillage option for RlmX-cultivars and for the other cultivars, and temporal
259 synchrony (for the RlmX-isolation strategy only). Analysis of variance was performed for
260 each strategy, considering all factors as categorical. The contribution of each factor was
261 assessed by the Mean Squared Error (MSE), which corresponds to the sum of squares divided
262 by the associated number of degrees of freedom (df). The significance of each factor was
263 tested using F-tests, and model goodness-of-fit was evaluated by the adjusted R^2 and the error
264 size of the residuals (RMSE, Root Mean Square Error). Model residuals were checked for
265 symmetry and normality, and independence from fitted values.

266 In the second set of analyses, we built regression trees to identify the best performing
267 combinations of factors, using the same explanatory factors as for variance analysis. One
268 regression tree was built for each evaluation criteria, considering the two isolation strategies
269 separately, using the CART method. This method recursively partitions the data in two groups
270 to minimize within-group variability while maximizing between-group variability, choosing
271 one factor at a time (Breiman *et al.*, 1984). Trees were selected using a modal tree based on
272 100 cross-validations (Breiman *et al.*, 1984), and final trees were pruned according to the 1-
273 standard error rule to avoid data over-fitting. For each explanatory factor in the final tree,
274 factor splitting was applied (Breiman *et al.*, 1984; Therneau *et al.*, 2015), calculating an index

275 of factor importance that corresponds to the sum of the deviance decrease at each node. Six
276 final trees were built, corresponding to the three evaluation criteria for the two isolation
277 strategies. New analyses of variance were performed for these six final trees, using the groups
278 as explanatory factors. The difference between groups was tested with Bonferroni least
279 significance difference (LSD) when the group-based analysis of variance was significant
280 ($p < 0.05$).

281 Analyses were performed with the R software version 3.2.3 (R Development Core Team,
282 2015), using the package “rpart” (Therneau *et al.*, 2015) for regression tree and the package
283 “agricolae” (de Mendiburu, 2016) for LSD tests.

284

285 3. Results

286 3.1. Crop mosaics

287 The two crop rotations designed by local stakeholders led to an objective of 334 ha of winter
288 oilseed rape (WOSR) grown annually for the 5-year rotation, and 239 ha of WOSR for the 7-
289 year rotation. Slightly higher WOSR acreages over the simulation years could be achieved
290 (e.g., for 0 m isolation distance, see Table 2). The field map used for simulation is a real-
291 world map (Figure 2), with field size ranging between 0.91 ha and 37.61 ha, for an average of
292 $10.58 \text{ ha} \pm 6.85 \text{ ha}$.

293 For WOSR isolation strategy, the WOSR acreage objective was only achieved for the three
294 replicates of the 7-year rotation of the 0 m isolation distance (i.e., contiguous fields), and it
295 was associated with low between-year variability (3-9 ha, Table 2). For the 5-year rotation,
296 the contiguous fields forbidding rule (0 m isolation distance) led to WOSR acreages that were
297 about 10% lower than the objective (annual average of 301 ha compared to a 334 ha
298 objective, Table 2), and were associated with a high between-year variability (33-60 ha, Table
299 2). WOSR acreage objectives for WOSR isolation strategy were not met for the 500 m and

300 1,000 m isolation distances, for the two rotations. For the 5-year rotation, WOSR acreages
301 were lower than the objective by 26-30% and 30-31% respectively, for the 500 m and 1,000
302 m isolation distances. These mosaics also highlighted high between-year variability, of about
303 70 ha for and 140 ha for 500 m and 1,000 m isolation distances, respectively (Table 2).
304 Similarly, the WOSR acreage objective associated with the 7-year rotation was not met for
305 the 500 m and 1,000 m isolation distances. However, the obtained acreages were closer to the
306 objective of 14.3% WOSR annually, with on average 12-13% WOSR for the 500 m isolation
307 distance, and 11-12% for the 1,000 m distance. For all isolation distances, the WOSR
308 between-year variability was lower in the 7-year rotation mosaics than in the 5-year rotation
309 mosaics (Table 2). For WOSR isolation strategy, the 15% of RlmX-cultivars were based on
310 WOSR acreages, and were lower than the objective for all isolation strategies, except for the 0
311 m isolation distance in the 7-year rotation. Between-replicates variability increased with the
312 isolation distance (Table 2).
313 For RlmX isolation strategy, WOSR acreage objectives were achieved for the two rotations
314 and the three isolation distances (Table 2), because the isolation distances were only applied
315 to 15% of WOSR fields (those grown with RlmX-cultivars). Thus both WOSR and RlmX-
316 cultivar acreages were stable throughout the rotations and the isolation distances for the RlmX
317 isolation strategy. Between-year and between-replicate variabilities were lower in this
318 strategy as compared to the WOSR isolation strategy.

319

320 # Table 2 approximately here #

321

322 3.2. Performance of WOSR isolation strategy

323 The simulations of WOSR-isolation strategy that were performed with the model SIPPOM-
324 WOSR resulted in a wide range of values for the three evaluation criteria, averaged over the

325 simulation years. Pathogen population size ranged between 4.5×10^{12} spores and 1.6×10^{15}
326 spores; the fraction of virulent pathotypes on RlmX-gene ranged between 9.5% and 81.3%,
327 and yield loss ranged between 1.5% and 7.6%. Yield loss increased with an increase of the
328 pathogen population size, but not with an increase of the fraction of virulent pathotypes on
329 RlmX-gene (Figure 3).

330

331 # Figure 3 approximately here #

332

333 All models used for variance analysis explained more than 82% of the evaluation criteria
334 variability, and were associated with low root mean squared errors (Table 3). The analyses of
335 variance performed on simulations for WOSR isolation strategy highlighted a highly
336 significant effect ($p < 0.001$) of isolation distance (0 m, 500 m, or 1,000 m), tillage on WOSR
337 stubble of both RlmX- and non-RlmX-cultivars, and rotation (5 and 7-year). Tillage on non-
338 RlmX-cultivars was the most explanatory factor (Table 3). The size of the pathogen
339 population was significantly lower for this factor when the stubble of non-RlmX-cultivars (i.e.
340 85% of WOSR) was ploughed (Modality “MB” of the factor “Till.other” of Figure 4A;
341 Appendix A). For the fraction of virulent pathotypes on RlmX-gene (avr_{lmX}), tillage on both
342 types of cultivars had a highly significant impact ($p < 0.001$), while the isolation distance and
343 the rotation had significant ($p < 0.05$) and non-significant effects ($p > 0.05$), respectively (Table
344 3). Ploughing the stubble of RlmX-cultivars significantly decreased the fraction of virulent
345 pathotypes on RlmX-gene, as compared to the two other tillage options, while ploughing the
346 stubble of non-RlmX-cultivars significantly increased this fraction (Appendix A, Figure 4C).
347 Isolation distance and tillage on non-RlmX-cultivars were the most important factors (highest
348 MSE) for yield loss; as with tillage on RlmX-cultivars, they had a highly significant impact
349 (Table 3). For instance, changing from 0 m to 1,000 m distance decreased average yield loss

350 by 1.5% (Appendix A, Figure 4C). Increasing WOSR frequency in the landscape from 7- to
351 5-year rotation increased yield loss significantly ($p < 0.05$, Table 3) by about 0.2%.

352

353 # Figure 4 approximately here #

354

355 # Table 3 approximately here #

356

357 The results of the variance analyses revealed that the most efficient combinations for
358 minimizing simulated values differed between the three evaluation criteria. However, the
359 tillage option on non-RlmX-cultivars always constituted the main factor, and therefore the
360 first node for the three regression trees (Figure 5). In this node, the ‘mouldboard ploughing’
361 modality was opposite to the ‘reference’ and ‘2 passages of stubble breaker’ modalities. The
362 tillage option on RlmX-cultivars was the second factor explaining the fraction of virulent
363 pathotypes on RlmX-gene. The second explaining factor for the evaluation criteria of
364 Population size and Yield loss was the isolation distance (Figure 5, Table 4). Isolation
365 distance was not selected as a main explanatory factor of the RlmX-virulent fraction. Rotation
366 length was selected as an important factor only for the Size of the Pathogen Population
367 (Figure 5, Table 4). Overall, the smallest pathogen population was simulated when ploughing
368 stubble of non-RlmX-cultivars. Combining isolation distance of 0 m and the most intensive
369 rotation (5-year) led to the highest population (Figure 5). Ploughing stubble of RlmX-
370 cultivars but not those of non-RlmX-cultivars led to the lowest RlmX-virulent fraction, and
371 the inverse ploughing rule led to the highest. Note that no significant differences of avrlmX
372 were detected when the stubble management of both types of cultivar did not differ (Figure
373 5). Finally, yield loss was significantly lower (3.2%) for the largest isolation distance (1,000

374 m) and ploughing of non-RlmX-cultivars, as compared to low isolation distance (0 m) and no
375 ploughing of non RlmX-cultivars (yield loss of 6.4%) (Figure 5).

376

377 # Figure 5 approximately here #

378

379 # Table 4 approximately here #

380

381 3.3. Performance of RlmX-cultivar isolation strategy

382 This strategy also led to a wide range of values for the three evaluation criteria. Although the
383 range was not as wide as in the WOSR isolation strategy, the simulated values were generally
384 higher, with the size of the pathogen population ranging between 9.9×10^{12} spores and $2 \times$
385 10^{15} spores, the fraction of virulent pathotypes on RlmX-gene ranging between 14% and 81%,
386 and yield loss ranging between 3.7% and 7.9% (Figure 6). Similar to the WOSR isolation
387 strategy, higher yield losses were associated with larger pathogen population sizes, but not
388 always with larger fractions of virulent pathotypes on RlmX gene (Figure 6).

389

390 # Figure 6 approximately here #

391

392 The ranking of the importance of explanatory factors in the RlmX-cultivar isolation strategy
393 differed from that in the WOSR-isolation strategy, however tillage on non-RlmX-cultivars
394 remained the main factor (highest MSE, Table 5). Tillage on RlmX-cultivars also had a
395 significant effect on the three evaluation criteria. Isolation distance had a significant impact
396 on yield loss only ($p < 0.05$, Table 5), which varied, as distance increased (Figure 7, Appendix
397 B). Increasing rotation length significantly decreased both yield loss and the size of the
398 pathogen population ($p < 0.001$) (Table 5). Synchronism of RlmX-cultivars significantly

399 decreased the fraction of virulent pathotypes on RlmX-gene, but it was not significant for the
400 two other evaluation criteria (Table 5). All models largely explained the variability of the
401 evaluation criteria (>92%), and were associated with low root mean squared errors (Table 5).

402

403 # Figure 7 approximately here #

404

405 # Table 5 approximately here #

406

407 As in WOSR isolation strategy, tillage of non-RlmX stubble was the first explanatory factor
408 for the three evaluation criteria (Table 6, Figure 8). Tree branching of RlmX-virulent fraction
409 was similar to that for WOSR isolation strategy, leading to significantly different averages
410 (17% and 77%) of virulent pathotypes on RlmX-gene for the two extreme groups (Figure 8).
411 Isolation distance did not constitute any node for either Population Size or Yield loss (Table
412 6). Rotation length was the second most important factor for grouping Population size and
413 Yield loss, together with tillage on RlmX-stubble for the latter (Figure 8). For all evaluation
414 criteria, within-group variability was lower as compared to that obtained for the trees of
415 WOSR isolation strategy.

416

417 # Figure 8 approximately here #

418

419 # Table 6 approximately here #

420

421 4. Discussion

422 4.1. Tillage and cultivar effects

423 This study assessed three complementary evaluation criteria in order to quantify the effect of
424 various stakeholder-designed strategies for the control of phoma stem canker of winter oilseed
425 rape. We found that the effectiveness of the strategies varied according to the evaluation
426 criteria in a manner consistent with Hossard *et al.* (2015b), who assessed mosaics with
427 random crop allocations, unlike the rule-based mosaics assessed in our study. In our study,
428 deep tillage (mouldboard ploughing of stubble) on non-RlmX-cultivars (i.e. not harbouring
429 the specific resistance gene RlmX) was the main lever for decreasing the size of the pathogen
430 population and yield loss due to phoma stem canker, but conversely, led to increased
431 breakdown in RlmX resistance (i.e. higher frequency of virulent pathotypes on RlmX-gene).
432 This opposing result is primarily linked to the high level of quantitative resistance harboured
433 by non-RlmX-cultivars, leading to less disease, lower yield loss, and in turn, to fewer
434 pathogens in the following year (Lô-Pelzer *et al.*, 2009) as compared to RlmX-cultivars (here
435 associated with a lower level of quantitative resistance). In parallel, within a unique mosaic,
436 deep tillage applied only on fields grown with RlmX-cultivars was better at preserving RlmX
437 resistance (i.e. smaller fraction of resistant pathogen population), while deep tillage on non-
438 RlmX-cultivars led to less preservation of RlmX resistance gene by mechanically favouring
439 spores resistant to RlmX (since only resistant spores can develop), as suggested by Hossard *et*
440 *al.* (2015a). Similarly, in a four-year experiment, Daverdin *et al.* (2012) found a rapid
441 evolution of pathogen population towards resistance to Rlm7-gene when residues of Rlm7-
442 cultivars were chiselled (minimum tillage) and sensitive cultivars (i.e. without Rlm7-gene)
443 were ploughed. This opposite result highlights the independence between the two evaluation
444 criteria regarding the genetic structure and the size of the pathogen population, in accordance
445 with findings of previous modelling studies on phoma stem canker (Hossard *et al.*, 2015b),
446 and on other crop pathogens. For instance, Papaix *et al.* (2015) highlighted that landscape

447 structures promoting large pathogen populations led to lower adaptation potential in their
448 host.

449 Previous studies on phoma stem canker of winter oilseed rape, or on other wind-dispersed
450 fungus diseases (e.g., *Puccinia triticina* responsible for wheat leaf rust), highlighted the major
451 effects of landscape composition in terms of acreages of the considered crop and/or of the
452 different host cultivars (level and type of resistance) on disease spread and impacts (e.g.,
453 Hossard *et al.*, 2015a; Papaïx *et al.*, 2011). In our study, only the frequency of the host crop
454 was tested (linked to the rotation period). Increasing WOSR acreages led to a significant
455 increase of yield loss and the size of the pathogen population in the two tested strategies
456 (WOSR- or RlmX-cultivar isolation), but never on the frequency of virulent pathotypes on
457 RlmX-gene (as RlmX frequency remains stable in our simulations). The frequency of RlmX-
458 cultivars in the landscape was highlighted as the main explanatory factor of the pathogen
459 population genetic structure of *Leptosphaeria maculans* (Hossard *et al.*, 2015a using a
460 modelling approach; Rouxel *et al.*, 2003 using field survey). Adding this variable to the
461 simulation framework, co-designed here with stakeholders, could highlight the effectiveness
462 of other combinations of cropping practices defined in time and space. In particular, Hossard
463 *et al.* (2015a) showed that the fraction of virulent pathotypes on RlmX-gene depended
464 primarily on the tillage option on RlmX-cultivars at low incidences of these cultivars in
465 agricultural landscapes, and reciprocally by tillage options on non-RlmX-cultivars at higher
466 incidences of RlmX-cultivars, as found here. The behaviour of the genetic structure in the
467 pathogen population could be explored by combining the rules tested here with higher
468 proportions of RlmX-cultivars at the landscape scale.

469

470 4.2. Spatial effects

471 Simulations of crop mosaics involving isolation distances are strongly dependent on the
472 modelling framework used, in our case, the SIPPOM-WOSR (Lô-Pelzer *et al.*, 2010a, 2010b).
473 This model had previously revealed its potential for simulating the impact of spatial
474 distribution of WOSR and associated cropping practices on disease severity in winter oilseed
475 rape with preliminary simulations of WOSR-isolation on simplified landscapes (Lô-Pelzer *et*
476 *al.*, 2010b). The dispersal curve produced in SIPPOM-WOSR has been found to be consistent
477 with dispersal kernels of *Leptosphaeria maculans* determined in field experiments, especially
478 for distances exceeding 100 m (Bousset *et al.*, 2015), and depending on weather conditions
479 (wind speed). Spatial effects also depend on landscape configuration, e.g., hedges potentially
480 acting as barriers. These elements were not taken into account in our study, while they could
481 decrease dispersal, and consequently the size of the pathogen population and yield loss.

482 4.2.1. WOSR isolation strategy

483 Based on the rapid decrease in spore dispersal and disease severity that was observed over the
484 first hundred meters (Salam *et al.*, 2001 and Marcroft *et al.*, 2004, respectively), Marcroft *et*
485 *al.* (2004) recommended distances between WOSR stubble (source) and sown WOSR (target)
486 of at least 100 m, and preferably 500 m. Our work identified isolation distances as the second
487 most important factor (after tillage of stubble) affecting the size of the pathogen population
488 and yield loss in the simulations of a WOSR-isolation strategy. Adjacent fields (0 m isolation
489 distance) led to higher yield loss and larger pathogen population, when compared to 500 m
490 and 1,000 m isolation distance. These findings are consistent with the systematically higher
491 infection levels of adjacent fields observed by Marcroft *et al.* (2004). For the WOSR-isolation
492 strategy, regression trees highlighted lower yield loss for 1,000 m isolation distance when
493 compared to 500 m, and the analysis of variance revealed a significant decrease of virulent
494 pathotypes on the RlmX-gene between 500 m and 1,000 m (Appendix A). These results differ
495 from the observations of Marcroft *et al.* (2004), who found a decline in disease severity from

496 100 m to 500 m, but no significant decrease between 500 m and 1,000 m. They however did
497 not detail cultivars and resistance characteristics, while, in our simulations, lower resistance
498 breakdown at 1,000 m could explain the lower yield loss. Other explanatory factors could be
499 linked to weather conditions (wind intensity and direction), which were not detailed in
500 Marcroft *et al.* (2004), but are important parameters for dispersal (Bousset *et al.*, 2015) and
501 subsequent phoma evaluation criteria (Hossard *et al.*, 2015b).

502 4.2.2. RlmX-cultivars isolation strategy

503 For the RlmX-isolation strategy, isolation distances were significant only in terms of yield
504 loss, and were not highlighted as a main factor in the corresponding regression tree. In this
505 case, simulated yield loss was significantly higher for the 500 m isolation distance than for the
506 0 m isolation distance, while no significant differences were found between 0 m and 1,000 m,
507 and between 500 m and 1,000 m. This potentially inconsistent result may be an artefact of
508 mosaics design (non-RlmX field location) since the isolation distance for this strategy was
509 only set for RlmX-cultivars (15% of the winter oilseed rape cultivation). In this strategy, the
510 main effect expected by local stakeholders concerned the genetic structure of the pathogen
511 population (i.e., the RlmX-virulent pathotypes) considered to be an indicator of resistance
512 durability. We found that isolating RlmX-cultivars had no effect on this evaluation criterion.
513 This may be consistent with previous findings of Travadon *et al.* (2011) who found high gene
514 flow among *Leptosphaeria maculans* populations in France, which could be due to high
515 dispersal rates or large population sizes.

516

517 4.3. Mosaic realism and feasibility

518 In our study, local stakeholders designed management strategies that involved two different
519 scales: (1) the field, mainly through stubble management depending on cultivar choice, and
520 (2) the landscape, through isolation distances between source and target fields. The rotation

521 length was defined at field scale, but also affected the landscape scale through the frequency
522 of winter oilseed rape crops within the region. WOSR acreage has continuously increased in
523 the Picardie NUTS-2 region since 1993, and currently accounts for about 9.6% of arable land
524 (Agreste, 2013, 2014). This indicates a trend of shorter crop rotations, leading to more
525 frequent cultivation of winter oilseed rape, which is consistent with the hypotheses of
526 stakeholders involved in this study. In terms of WOSR stubble management, local
527 stakeholders built rules involving either small changes (two passages of stubble breaker) or
528 major changes (use of mouldboard ploughing) for comparison to the designed reference
529 situation, where WOSR stubble was not ploughed before the following crop, as WOSR results
530 in a good soil structure (Chan and Heenan, 1996). Although very efficient for burying stubble,
531 and thus limiting inoculum production (Schneider *et al.*, 2006), the implementation of
532 mouldboard ploughing after WOSR would represent a significant change in management,
533 implying the need for new ploughing equipment, and the reorganization of work at farm scale.
534 This points to one of the limits of this study in that farms are not represented in the simulation
535 model used. Farms could be represented, as suggested for another spatially-explicit model by
536 Vinatier *et al.* (2012), by adding a sub-model considering farmers as agents with their specific
537 decision rules, concerning work organization (e.g., Attonaty *et al.*, 1993; Jeuffroy *et al.*,
538 2012), and crop choices and allocation (e.g., Matthews, 2006). Indeed, the crop isolation rules
539 tested here led to crop clustering effects from one year to the next, an effect that increased
540 with the isolation distance. Such crop aggregation could be difficult to set up in practice, since
541 crop mosaics are primarily built through crop clustering effects due to the organization of
542 crop rotation at the farm scale (Thenail *et al.*, 2009; Schaller *et al.*, 2012). In the Picardie
543 NUTS-2 region, the average farm size increased from 88 ha to 102 ha between 2000 and 2010
544 (Agreste, 2013), and frequent merging of fields has occurred in the region since the 1950s
545 (Philippe and Polombo, 2009), leading to farms with grouped fields. This means that the

546 isolation distance strategy would require the farmer to dedicate a large part of his land to
547 WOSR in one given year, and forego growing it the next year. This could lead to work
548 organization issues, to increase the farmer's risks and dependence on market prices, and also
549 to negative impacts on other pest and diseases (e.g., on attacks by root maggot and pollen
550 beetle in Valantin-Morison *et al.*, 2007), and thus does not seem realistic. Implementing
551 isolation practices would also require increased coordination in year-to-year planning, and
552 coordination between neighbouring farmers' management and cropping plans, which is not
553 currently the case. Moreover, designed crop mosaics for the WOSR-isolation strategy did not
554 all lead to the annual acreage objective, thus highlighting the difficulty of organizing WOSR
555 in time and space to respect the constraints of isolation distances. As suggested by Castellazzi
556 *et al.* (2010), this points to the need to test the 'physical' feasibility of spatio-temporal
557 constraints, which depend on field patterns within the landscape, in order to evaluate the
558 'optimality' of various crop arrangements. Taking explicitly into account farms could help to
559 assess the 'real' world feasibility of efficient crop mosaics for phoma control, and in turn lead
560 to the design of a landscape-based Decision Support System representing farms explicitly.
561 Two concepts are usually included in farm or landscape decision support models, i.e. the
562 cropping plan (spatial dimension) and the decisions for crop rotation (temporal dimension)
563 (Dury *et al.*, 2012). Farmers' decisions are defined at different temporal scales, from tactical
564 (intra-) annual decisions (e.g. crop allocation, crop management) to structural multi-year
565 decisions (e.g. crop rotation) (Risbey *et al.*, 1999), and drive the dynamic spatial distribution
566 of crops and associated practices at landscape scale (Dury *et al.*, 2012). Our results could be
567 included in a decision support system bases on this information and field observations, in
568 order to advise individual farmers on the potential phoma risk due to previous year WOSR
569 and cultivar locations. This type of tool could then be used to facilitate the identification of
570 infected fields for mouldboard ploughing (i.e., to limit epidemics expansion), and the

571 implementation of isolation strategies with neighbouring farms, depending on other local
572 pests (e.g., pollen beetle), and farm constraints.

573

574 5. Conclusion

575 We showed in this study that stubble management was a key practice for phoma control,
576 although displaying opposite results with ploughing of non-RlmX residues leading to lower
577 yield loss and size of the pathogen population, but higher resistance breakdown. Combining
578 intensive stubble management while isolating WOSR source and target fields was even more
579 efficient in controlling the disease, while RlmX-cultivar isolation was not. Large isolation
580 distances between WOSR fields increased phoma control, but did not allow achieving annual
581 WOSR acreages' objectives.

582 These results indicate possible trade-offs on phoma control between short- and long-term
583 objectives, i.e. yield loss (impacting mostly farmers and crop collectors) and resistance
584 durability (impacting mostly crop collectors and crop breeders), respectively. They also
585 highlight that the combination of field (tillage) and landscape (isolation) factors are promising
586 levers for phoma control. These two management strategies contribute to different types of
587 advice for farmers: cultivar-dependent WOSR management for tillage, and spatial rules for
588 isolation. These types of strategies are proposed when compared to current one, mostly
589 relying on cultivar choice (resistance) and delay return (of both WOSR and resistance), with
590 no technical information with regards to spatial deployment. A promising perspective to this
591 study would be the design of a decision support tool to facilitate phoma risk quantification,
592 and further advice priority (infected) fields to be either ploughed or isolated for next year
593 WOSR cultivation.

594

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601 References

602 Agreste, 2013. Picardie-Recensement agricole 2010. Les “grandes cultures” en
603 Picardie. Agreste Picardie – Les feuilles de liaisons, n°47. [http://draaf.hauts-de-](http://draaf.hauts-de-france.agriculture.gouv.fr/IMG/pdf/Picardie_-_grandes_-_cultures_cle87e713.pdf)
604 [france.agriculture.gouv.fr/IMG/pdf/Picardie - grandes - cultures_cle87e713.pdf](http://draaf.hauts-de-france.agriculture.gouv.fr/IMG/pdf/Picardie_-_grandes_-_cultures_cle87e713.pdf) (Accessed:
605 January 2016).

606 Agreste, 2014. Website of Agreste, <http://www.agreste.agriculture.gouv.fr> (Accessed:
607 December 2014).

608 Attonaty, J.-M., Chatelin, M.-H., Mousset, J., 1993. A decision support system based
609 on farmers' knowledge to assess him in decision-making about work organization and long
610 term evolution. In: EurAgEng, October 1–2, 1993, Firenze, Italy.

611 Aubertot, J.N., Pinochet, X., Doré, T., 2004. The effects of sowing date and nitrogen
612 availability during vegetative stages on *Leptosphaeria maculans* development on Winter
613 OilSeed Rape. *Crop Protection*, 23(7), 635-345.

614 Aubertot, J.N., West, J.S., Bousset-Vaslin, L., Salam, M.U., Barbetti, M.J., Diggle,
615 A.J., 2006. Improved resistance management for durable disease control: A case study of
616 phoma stem canker of oilseed rape (*Brassica napus*). *European Journal of Plant Pathology*,
617 114, 91-106.

618 Baessler, C., Klotz, Z., 2006. Effects of changes in agricultural land-use on landscape
619 structure and arable weed vegetation over the last 50 years. *Agriculture, Ecosystems and*
620 *Environment*, 115, 43-50.

621 Bivand, R., Lewin-Koh, N., 2016. Maptools : Tools for Reading and Handling Spatial
622 Objects. R package version 0.8-39. <https://CRAN.R-project.org/package=maptools>
623 (Accessed: December 2016).

624 Bivand, R., Rundel, C., 2016. Rgeos : Interface to Geometry Engine – Open Source
625 (GEOS). R package version 0.3-19. <https://CRAN.R-project.org/package=rgeos> (Accessed:
626 December 2016).

627 Bokor, A., Barbetti, M.J., Brown, A.G.P., Mac Nish, G.C., Wood, P.McR., 1975.
628 Blackleg of rapeseed. *Journal of Agriculture, Western Australia*, 16, 7-10.

629 Bousset, L., Jumel, S., Garreta, V., Picault, H., Soubeyrand, S., 2015. Transmission of
630 *Leptosphaeria maculans* from a cropping season to the following one. *Annals of Applied*
631 *Biology*, 166, 530-243.

632 Brandenbourg, A.M., Carrol, M.S., Blatner, K.A., 1995. Towards successful forest
633 planning through local based qualitative sociology. *Western Journal of Applied Forestry*,
634 10(3), 95-99.

635 Breiman, L., Friedman, J.H., Olshen, R.A., Stone, C.J., 1984. Classification and
636 Regression Trees. Chapman and Hall. Wadsworth, Inc., New York, USA.

637 Castellazzi, M.S., Matthews, J., Angevin, F., Sausse, C., Wood, G.A., Burgess, P.J.,
638 Brown, I., Conrad, K.F., Perry, J.N., 2010. Simulation scenarios of spatio-temporal
639 arrangement of crops at the landscape scale. *Environmental Modelling and Software*, 25,
640 1881-1889.

641 Chan, K.Y., Heenan, D.P., 1996. The influence of crop rotation on soil structure and
642 soil physical properties under conventional tillage. *Soil & Tillage Research* 37, 113-125

643 Charnell, M.A., 2008. An individual-based model of a tritrophic ecology. *Ecological*
644 *Modelling*, 218, 195-206.

645 Colbach, N., Devaux, C., Angevin, F., 2009. Comparative study of the efficiency of

646 buffer zones and harvest discarding on gene flow containment in oilseed rape. A modelling
647 approach. *European Journal of Agronomy*, 30, 187-198.

648 Daverdin, G., Rouxel, T., Gout, L., Aubertot, J.N., Fudal, I., Meyer, M., Parlange, F.,
649 Carpezat, J., Balesdent, M.H., 2012. Genome structure and reproductive behavior influence on
650 the evolutionary potential of a fungal phytopathogen. *Plos One* 8, e1003020.

651 Delourme, R., Chevre, A.M., Brun, H., Rouxel, T., Balesdent, M.H., Dias, J.S.,
652 Salisbury, P., Renard, M., Rimmer, S.R., 2006. Major gene and polygenic resistance to
653 *Leptosphaeria maculans* in oilseed rape (*Brassica napus*). *European Journal of Plant*
654 *Pathology* 114 (1), 41-52.

655 de Mendiburu, F., 2016. *Agricolae: Statistical procedures for Agricultural Research*. R
656 package version 1.2-4. <https://CRAN.R-project.org/package=agricolae> (Accessed: January
657 2017).

658 Dury, J., Schaller, N., Garcia, F., Reynaud, A., Bergez, J.E., 2012. Models to support
659 cropping plan and crop rotation decisions. A review. *Agronomy for Sustainable Development*,
660 32, 567-580.

661 Fitt, B.D.L., Brun, H., Barbetti, M.J., Rimmer, S.R., 2006. World-wide importance of
662 phoma stem canker (*Leptosphaeria maculans* and *L.-biglobosa*) on oilseed rape (*Brassica*
663 *napus*). *European Journal of Plant Pathology*, 114, 3-15.

664 Gladders, P., Evans, N., Marcroft, S., Pinochet, X., 2006. Dissemination of
665 information about management strategies and changes in farming practices for the
666 exploitation of resistance to *Leptosphaeria maculans* (phoma stem canker) in oilseed rape
667 cultivars. *European Journal of Plant Pathology*, 114, 117-126.

668 Gosme, M., de Villemandy, M., Bazot, M., Jeuffroy, M.H., 2012. Local and
669 neighbourhood effects of organic and conventional wheat management on aphids, weeds, and
670 foliar diseases. *Agriculture, Ecosystems and Environment*, 161, 121-129.

671 Hall, R., 1992. Epidemiology of blackleg of oilseed rape. Canadian Journal of Plant
672 Pathology-Revue Canadienne De Phytopathologie 14(1), 46e55.

673 Hijmans, R.J., van Ittersum, M.K., 1996. Aggregation of spatial units in linear
674 programming models to explore land use options. NJAS Wageningen Journal of Life
675 Sciences, 44, 145–162.

676 Hossard, L., Jeuffroy, L.H., Pelzer, E., Pinochet, X., Souchere, V., 2013. A
677 participatory approach to design spatial scenarios of cropping systems and assess their effects
678 on phoma stem canker management at a regional scale. Environmental Modelling and
679 Software, 48, 17-26.

680 Hossard, L., Gosme, M., Souchere, V., Jeuffroy, M.H., 2015a. Linking cropping
681 system mosaics to disease resistance durability. Ecological Modelling, 307, 1-9.

682 Hossard, L., Souchere, V., Pelzer, E., Pinochet, X., Jeuffroy, M.H., 2015b. Meta-
683 modelling of the impacts of regional cropping system scenarios for phoma stem canker
684 control. European Journal of Agronomy, 68, 1-12.

685 Jeuffroy, M.H., Vocanson, A., Roger-Estrade, J., Meynard, J.M., 2012. The use of
686 models at field and farm levels for the ex ante assessment of new pea genotypes. European
687 Journal of Agronomy, 42, 68-78.

688 Leenhardt, D., Angevin, F., Biarnes, A., Colbach, N., Mignolet, C., 2010. Describing
689 and locating cropping systems on a regional scale. A review. Agronomy for Sustainable
690 Development, 30, 131-138.

691 Legg, D.E., 2004. The relevance of modelling in successful implementation of IPM.
692 In: Koul, O., Dhaliwal, G.S. (Eds.), Integrated Pest Management: Potential, Constraints and
693 Challenges. Cabi Publication, Oklahoma State University, United States, pp. 39–54.

694 Lô-Pelzer, E., Aubertot, J.N., David, O., Jeuffroy, M.H., Bousset, E., 2009.
695 Relationship between severity of blackleg (*Leptosphaeria maculans*/L. *biglobosa* species

696 complex) and subsequent primary inoculum production on oilseed rape stubble. *Plant*
697 *Pathology*, 58, 61-70.

698 Lô-Pelzer, E., Aubertot, J.N., Bousset, L., Salam, M.U., Jeuffroy, M.N., 2010a.
699 SIPPOM- WOSR: a simulator for integrated pathogen population management of phoma stem
700 canker on winter oilseed rape. II. Sensitivity analysis. *Field Crops Research*, 118, 82–93.

701 Lô-Pelzer, E., Bousset, L., Jeuffroy, M.H., Salam, M.U., Pinochet, X., Boillot, M.,
702 Aubertot, J.N., 2010b. SIPPOM-WOSR: a simulator for integrated pathogen population
703 management of phoma stem canker on winter oilseed rape. I. Description of the
704 model. *Field Crops Research*, 118, 73–81.

705 Marcroft, S.J., Sprague, S.J., Pymer, S.J., Salisbury, P.A., Howlett, B.J., 2004. Crop
706 isolation, not extended rotation length, reduces blackleg (*Leptosphaeria maculans*) severity of
707 canola (*Brassica napus*) in south-eastern Australia. *Australian Journal of Experimental*
708 *Agriculture*, 44, 601-606.

709 Matthews, R., 2006. The People and Landscape Model (PALM): Towards full
710 integration of human decision-making and biophysical simulation models. *Ecological*
711 *Modelling*, 194, 329-343.

712 Meehan, T.D., Werling, B.P., Landis, D.A., Gratton, C., 2011. Agricultural landscape
713 simplification and insecticide use in the Midwestern United States. *Proceedings of the*
714 *National Academy of Sciences*, 108, 11500-11505.

715 Oerke, E.C., 2006. Crop losses to pests. *Journal of Agricultural Science*, 144, 31-43.

716 Oerke, E.C., Dehne, H.W., 2004. Safeguarding production – losses in major crops and
717 the role of crop protection. *Crop Protection*, 23, 275-285.

718 Papaix, J., Burdon, J.J., Zhan, J., Thrall, P.H., 2015. Crop pathogen emergence and
719 evolution in agro-ecological landscapes. *Evolutionary Applications*, 8, 385-402.

720 Papaix, J., Goyeau, H., Du Cheyron, P., Monod, H., Lannou, C., 2011. Influence of

721 cultivated landscape composition on variety resistance: an assessment based on wheat leaf
722 rust epidemics. *New Phytologist*, 191, 1095-1107.

723 Philippe, M.A., Polombo, N., 2009. Soiwante années de remembrement: Essai de bilan
724 critique de l'aménagement foncier en France. *Etudes foncières*, Compagnie d'édition
725 foncière, pp. 43-49.

726 Plissonneau, C., Daverdin, G., Ollivier, B., Blaise, F., Degrave, A., Fudal, I., Rouxel,
727 T., Balesdent, M.H., 2016. A game of hide and seek between avirulence genes *AvrLm4-7* and
728 *AvrLm3* in *Leptosphaeria maculans*. *New Phytologist*, 209, 1613-1624.

729 Primdahl, J., 1999. Agricultural landscapes as places of production and for living in
730 owner's versus producer's decision making and the implications for planning. *Landscape and*
731 *Urban Planning*, 46, 143-150.

732 R Development Core Team, 2015. R: A language and environment for statistical
733 computing. R foundation for Statistical Computing, Vienna, Austria. ISBN 3-9000051-07-0
734 (2011). <http://www.R-project.org> (Accessed: December 2016).

735 Reed, M.S., 2008. Stakeholder participation for environmental management: A
736 literature review. *Biological Conservation*, 141, 2417-2431.

737 Risbey, J., Kandlikar, M., Dowlatabadi, H., Graetz, D., 1999. Scale, context, and
738 decision making in agricultural adaptation to climate variability and change. *Mitigation and*
739 *Adaptation Strategies for Global Change*, 4(2), 137-165.

740 Rouxel, T., Penaud, A., Pinochet, X., Brun, H., Gout, L., Delourme, R., Schmit, J.,
741 Balesdent, M.H., 2003. A 10-year survey of populations of *Leptosphaeria maculans* in France
742 indicates a rapid adaptation towards the *Rlm1* resistance gene of oilseed rape. *European*
743 *Journal of Plant Pathology* 109 (8), 871-881.

744 Rusch, A., Valantin-Morison, M., Sarthou, J.P., Roger-Estrade, J., 2010. Integrating
745 crop and landscape management into new crop protection strategies to enhance biological

746 control of oilseed rape insect pests. In Biocontrol-Based Integrated Management of Oilseed
747 Rape Pests, pp. 415-448. Springer Netherlands.

748 Rusch, A., Valantin-Morison, M., Sarthou, J.P., Roger-Estrade, J., 2011. Multi-scale
749 effects of landscape complexity and crop management on pollen beetle parasitism rate.
750 Landscape Ecology, 23, 473-486.

751 Sadok, W., Angevin, F., Bergez, J.E., Bockstaller, C., Colomb, B., Guichard, L., Reau,
752 R., Messéan, A., Doré, T., 2009. MASC, a qualitative multi-attribute decision model for ex
753 ante assessment of the sustainability of cropping systems. Agronomy for sustainable
754 development, 29, 447-461.

755 Salam, M.U., Galloway, J., Khangura, R.K., Diggle, A.J., MacLeod, W.J., Barbetti,
756 M.J., 2001. Spatial spread of blackleg of canola – A regional scale simulation model. In
757 Conference Proceedings, 12th Australian Research Assembly on Brassicas, Geelong,
758 Victoria, Australia. pp. 101-105.

759 Schaller, N., Lazrak, E.G., Martin, P., Mari, J.F., Aubry, C., Benoit, M., 2012.
760 Combining farmers' decision rules and landscape stochastic regularities for landscape
761 modelling. Landscape Ecology, 27, 433-446.

762 Schneider, O., Roger-Estrade, J., Aubertot, J.N., Doré, T., 2006. Effect of seeders and
763 tillage equipment on vertical distribution of oilseed rape stubble. Soil & Tillage Research 85
764 (1e2), 115-122.

765 Skelsey, P., Rossing, W.A.H., Kessel, G.J.T., van der Werf, W., 2009. Scenario
766 approach for assessing the utility of dispersal information in decision support for aerially
767 spread plant pathogens, applied to *Phytophthora infestans*. Phytopathology, 99, 887-895.

768 Skelsey, P., Rossing, W.A.H., Kessel, G.J.T., van der Werf, W., 2010. Invasion of
769 *Phytophthora infestans* at the landscape level: how do spatial scale and weather modulate the
770 consequences of spatial heterogeneity in host resistance? Phytopathology, 100, 1146-1161.

771 Souchere, V., Millair, L., Echeverria, J., Bousquet, F., Le Page, C., Etienne, M., 2010.
772 Co- constructing with stakeholders a role-playing game to initiate collective management of
773 erosive runoff risks at the watershed scale. *Environmental Modelling & Software* 25, 1359-
774 1370.

775 Sprague, S.J., Marcroft, S.J., Hayden, H.L., Howlett, B.J., 2006. Major gene resistance
776 to blackleg in *Brassica napus* overcome within three years of commercial production in
777 southeastern Australia. *Plant Disease* 90 (2), 190-198.

778 Stabler, B., 2013. Shapefiles: Read and Write ESRI Shapefiles. R package version 0.7.
779 <https://CRAN.R-project.org/package=shapefiles> (Accessed: December 2016).

780 Stoate, C., Boatman, N.D., Borralho, R.J., Carvalho, C.R., de Snoo, G.R., Eden, P.,
781 2001. Ecological impacts of arable intensification in Europe. *Journal of Environmental*
782 *Management*, 63, 337-365.

783 Stuckenbrock, E.H., McDonald, B.A., 2008. The origins of plant pathogens in Agro-
784 ecosystems. *Annual Review of Phytopathology*, 47, 75-100.

785 Thenail, C., Joannon, A., Capitaine, M., Souchere, V., Mignolet, C., Schermann, N.,
786 Di Pietro, F., Pons, Y., Gaucherel, C., Viaud, V., Baudry, J., 2009. The contribution of crop-
787 rotation organization in farms to crop-mosaic patterning at local landscape scales.
788 *Agriculture, Ecosystems and Environment*, 131, 207-219.

789 Therneau, T., Atkinson, B., Ripley, B., 2015. Rpart: Recursive partitioning and
790 regression trees. R package version 4.1-10. <https://CRAN.R-project.org/package=rpart>
791 (Accessed: January 2017).

792 Travadon, R., Sache, I., Dutech, C., Stachowiak, A., Marquer, B., Bousset, L., 2011.
793 Absence of isolation by distance patterns at the regional scale in the fungal plant pathogen
794 *Leptosphaeria maculans*. *Fungal Biology*, 115, 649-659.

795 Valantin-Morison, M., Meynard, J.M., Doré, T., 2007. Effects of crop management
796 and surrounding field environment on insect incidence in organic winter oilseed rape
797 (*Brassica Napus* L.). *Crop Protection*, 26, 1108-1120.

798 Veldkamp, A., Kok, K., de Koning, G.H.J., Schoorl, J.M., Sonneveld, M.P.W.,
799 Verburg, P.H., 2001. Multi-scale system approaches in agronomic research at the landscape
800 scale. *Soil and Tillage Research*, 58, 129-140.

801 Vinatier, F., Gosme, F., Valentin-Morison, M., 2012. A tool for testing integrated pest
802 management strategies on a tritrophic system involving pollen beetle, its parasitoid and
803 oilseed rape at the landscape scale. *Landscape Ecology*, 27, 1421-1433.

804 Vinatier, F., Lagacherie, P., Voltz, M., Petit, S., Lavigne, C., Brunet, Y., Lescourret,
805 F., 2016. An unified framework to integrate biotic, abiotic processes and human activities in
806 spatially explicit models of agricultural landscapes. *Frontiers in Environmental Sciences*, 4, 6.

807 Voinov, A., Bousquet, F., 2010. Modelling with stakeholders. *Environmental*
808 *Modelling and Software*, 25, 1268-1281.

809 Wickham, H., 2009. *Ggplot2: Elegant Graphics for Data Analysis*. Springer New
810 York, 1(2), 3.

811 Williams, G.J., 2011. *Data mining with {Rattle} and {R}: The art of excavating data*
812 *for knowledge discovery*. Springer Science+Business Media, LLC. [https://cran.r-](https://cran.r-project.org/web/packages/rattle/index.html)
813 [project.org/web/packages/rattle/index.html](https://cran.r-project.org/web/packages/rattle/index.html) (Accessed: January 2017).

814 Figure captions

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838 Figure 8. Regression tree models of the three criteria for the RlmX-cultivar isolation strategy:
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840

Table 1. Summary of the characteristics of performed simulations for the two isolation targets (fields grown with WOSR or RlmX-cultivars)

Strategy	Information	Tillage (on non-RlmX/RlmX fields)	Isolation distance between fields	WOSR frequency ¹	Temporal synchrony	Replicates	Total
WOSR isolation	Number of options	9	3	2	NA	3	162
	Options	MB/MB; MB/ref; MB/2SB	0 m	14.3%	different spatial organization	3	
		ref/ref; ref/MB; ref/2SB	500 m	20%			
2SB/2SB; 2SB/MB; 2SB/ref	1000 m						
RlmX isolation	Number of options	9	3	2	2	3	324
	Options	MB/MB; MB/ref; MB/2SB	0 m	14.3%	synchrony	different spatial organization	
		ref/ref; ref/MB; ref/2SB	500 m	20%	asynchrony		
2SB/2SB; 2SB/MB; 2SB/ref	1000 m						

MB: Mouldboard ploughing; 2SB: 2 passages of stubble breaker; ref: reference tillage; ¹WOSR annual frequency correspond to the rotations designed by stakeholders: 5-year rotation (20%) and 7-year rotation (14.3%) with only one WOSR cultivation during the rotation.

Table 2. WOSR acreages of the three replicates of each isolation distance for RlmX- and WOSR-isolation strategies. Annual mean and standard deviation over the simulation years are indicated for each replicate.

Rotation	Objective (ha)	Isolation distance	WOSR isolation strategy: WOSR acreages (ha)	RlmX isolation strategy: WOSR acreages (ha)
5 years	334	0 m	301±33; 301±51; 301±60	334±5; 334±7; 334±7
		500 m	235±82; 239±74; 247±59	333±7; 334±4; 334±5
		1000 m	230±147; 231±143; 233±138	329±6; 332±8; 334±12
7 years	239	0 m	238±9; 243±3; 243±3	236±7; 237±3; 241±1
		500 m	200±53; 209±41; 220±49	238±5; 238±8; 239±6
		1000 m	179±89; 180±76; 207±49	239±7; 239±8; 243±5

Table 3. Analysis of variance of yield loss, frequency of virulent pathotypes on RlmX-cultivars, and size of the pathogen population for the strategies of WOSR field isolation.

Factor	d.f.	Size of pathogen population (spores)		Frequency of virulent pathotypes on RlmX-gene (%)		Yield loss (%)	
		MSE	p-value	MSE	p-value	MSE	p-value
Distance	2	1.173 x 10 ³⁰	<0.001	282.9	0.030	29.564	<0.001
Tillage RlmX	2	1.193 x 10 ³⁰	<0.001	10,658.1	<0.001	4.011	<0.001
Tillage Other	2	1.516 x 10 ³¹	<0.001	18,801.5	<0.001	57.510	<0.001
Rotation	1	4.422 x 10 ²⁹	<0.001	308.4	0.051	0.897	0.038
Adjusted R ²		0.954		0.8231		0.848	
RMSE		9.860 x 10 ¹³		8.671		0.739	

d.f.: number of degrees of freedom; MSE: Mean Squared Error; RMSE: Root Mean Squared Error; Tillage Other : tillage on non-RlmX cultivars.

Table 4. Tree main characteristics (importance of each factor and global relative error) for the three evaluation criteria of WOSR isolation strategies.

Factor	Size of pathogen population (spores)	Frequency of virulent pathotypes on RlmX-cultivars (%)	Yield loss (%)
Distance	2.964×10^{30}	-	63.436
Tillage RlmX	4.601×10^{29}	25,375.37	-
Tillage Other	2.946×10^{31}	37,574.33	113.483
Rotation	5.747×10^{29}	-	-
Relative error	0.07	0.13	0.17

-: this factor was not retained as informative in the final tree.

Table 5. Analysis of variance of yield loss, frequency of virulent pathotypes on RlmX-cultivars, and size of the pathogen population for the strategies of RlmX-cultivars field isolation.

Factor	d.f.	Size of pathogen population (spores)		Frequency of virulent pathotypes on RlmX-gene (%)		Yield loss (%)	
		MSE	p-value	MSE	p-value	MSE	p-value
Distance	2	7.187 x 10 ²⁶	0.945	9	0.752	0.300	0.019
Tillage RlmX	2	2.164 x 10 ³⁰	<0.001	24,244	<0.001	17.294	<0.001
Tillage Other	1	5.534 x 10 ³¹	<0.001	41,399	<0.001	228.273	<0.001
Rotation	1	1.024 x 10 ³¹	<0.001	42	0.251	26.904	<0.001
Synchronism	1	3.703 x 10 ²⁶	0.865	1,52	<0.001	0.008	0.748
Adjusted R ²		0.969		0.929		0.956	
RMSE		1.111 x 10 ¹⁴		5.544		0.269	

d.f.: number of degrees of freedom; MSE: Mean Squared Error; RMSE: Root Mean Squared Error; Tillage Other : tillage on non-RlmX cultivars.

Table 6. Tree main characteristics (importance of each factor and global relative error) for the three evaluation criteria of RlmX isolation strategies.

Factor	Size of pathogen population (spores)	Frequency of virulent pathotypes on RlmX-cultivars (%)	Yield loss (%)
Distance	-	-	-
Tillage RlmX	-	54,991.41	34.569
Tillage Other	1.117×10^{32}	82,619.31	450.724
Rotation	1.375×10^{31}	-	30.572
Synchronism	-	-	-
Relative error	0.04	0.04	0.05

-: this factor was not retained as informative in the final tree.

	<u>Method</u>	<u>Output</u>
<i>Step A</i>	Participatory collective design of management strategies for phoma control	Strategies combining WOSR/cultivar frequency ¹ and isolation ² and tillage options ³
<i>Step B</i>	Translation of strategies into field allocation of WOSR and cropping practices	Mosaics of crops, cultivars and associated tillage
<i>Step C</i>	Simulations of strategy-based mosaics with SIPPOM-WOSR	Mosaic assessment with 3 criteria: Yield loss, Size and genetic structure of the pathogen population
<i>Step D</i>	Statistical comparison of strategies for each criterion	Ranking of strategies regarding phoma control for each criterion

Figure 1. Steps for the design and comparison of control strategies.

¹Stakeholders designed two rotations (7- and 5-years) corresponding to an annual WOSR frequency of 14.3% and 20%, respectively.

²Stakeholders designed three isolation distances corresponding to buffer zones of 0 m (contiguous fields), 500 m and 1,000 m between source fields (WOSR of year y) and target fields (WOSR of year y+1). Isolation distances considered either all WOSR fields, either only RlmX-cultivars.

³Stakeholders designed specific tillage practices (to manage WOSR stubble) according to cultivar types (with or without RlmX qualitative resistance).

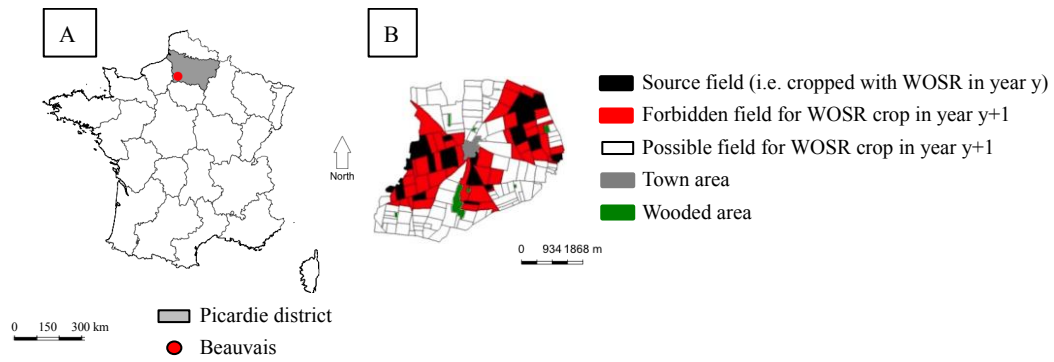


Figure 2. Location of (A) the study district (in grey) and landscape modelling support (red dot), and (B) example of landscape composition resulting from the rules for spatial allocation of WOSR fields in year y+1.

Town and wooded area are indicated in grey and green, respectively.

Maps were done with the R software (R Development Core team, 2015) and the R packages ‘maptools’ (Bivand and Lewin-Koh, 2016) and ‘shapefiles’ (Stabler, 2013).

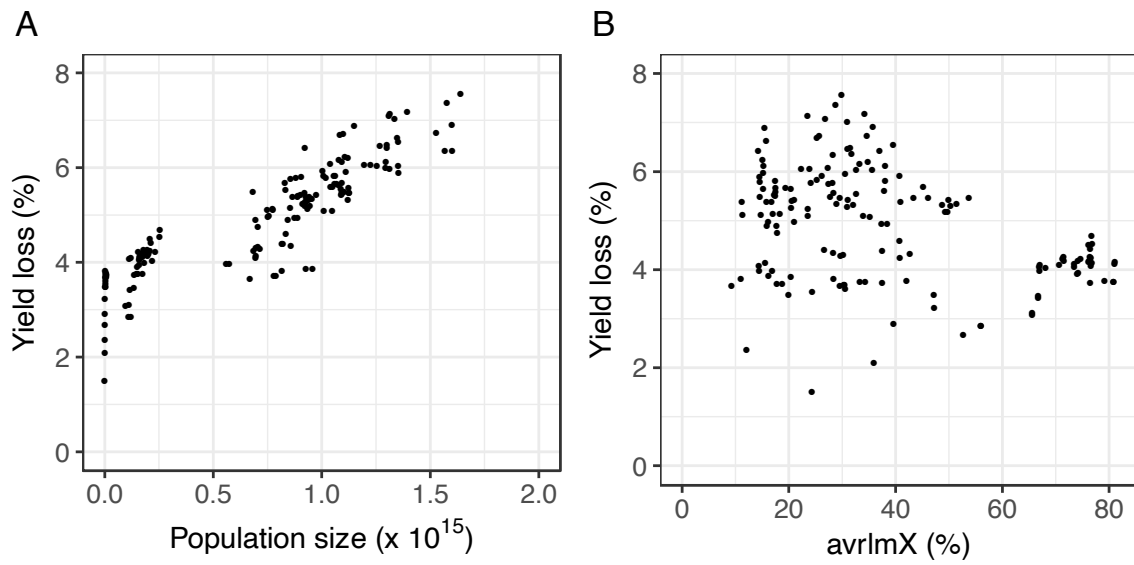


Figure 3. Simulation results for WOSR isolation strategy. Yield losses are plotted against size of the pathogen population (A) and frequency of virulent pathotypes on RlmX-gene (avrImX, B).

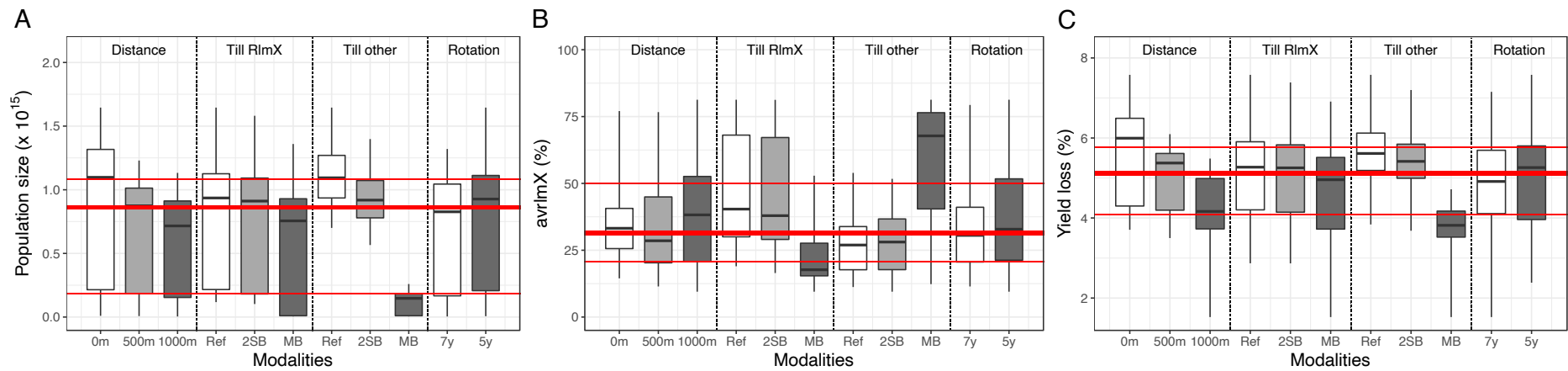


Figure 4. Boxplots of simulated values for Population size (A), Frequency of the virulent pathotypes on RlmX-cultivars (B), and Yield loss (C) for the WOSR isolation strategy. Extreme values correspond to minimum and maximum simulated values. Red lines indicate the global median (bold line), 25th and 75th quantiles of simulated values for the corresponding variable and isolation strategy. Till. RlmX: tillage on RlmX-cultivars; Till. Other: tillage on non-RlmX cultivars; Ref: reference tillage; 2SB: 2 stubble breakers; MB: Mouldboard ploughing; 7y: 7-year rotation; 5y: 5-year rotation. Colours of boxplot distinguish the modalities of a factor. Figures were realized with ‘ggplot2’ R package (Wickham, 2009).

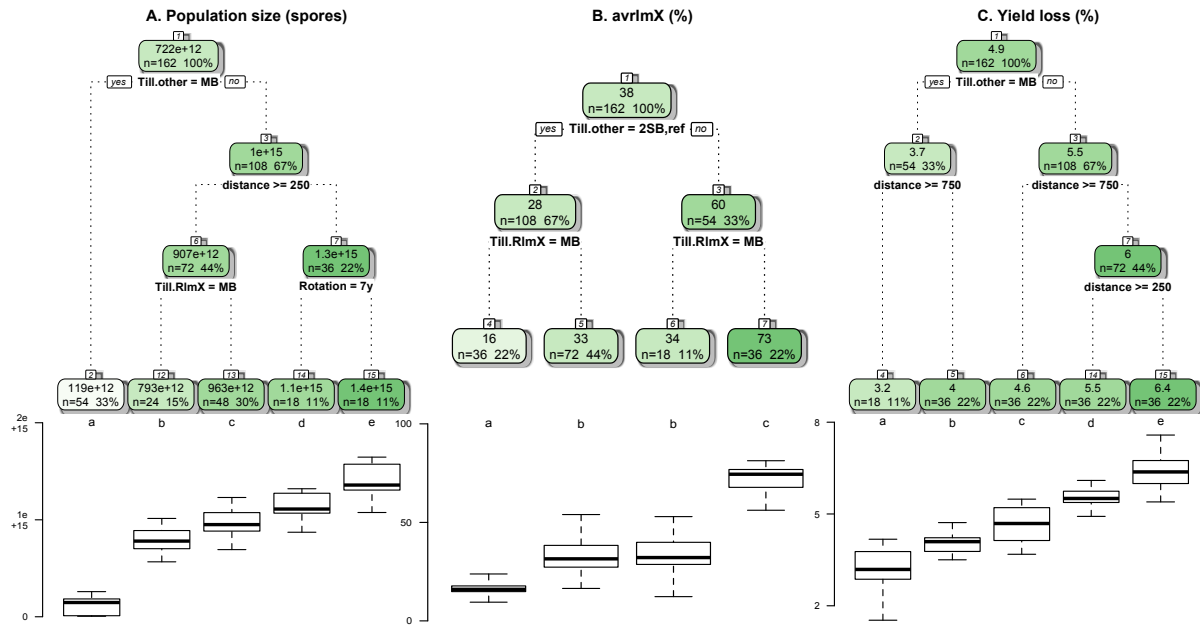


Figure 5. Regression tree models of the three evaluation criteria for the WOSR isolation strategy: Population size (A), avrlmX (B) and Yield loss (C). For each group, the 1st number indicates the group mean, the 2nd number (n) indicates the number of simulations, and the 3rd its corresponding percentage. The criterion distribution for each group is indicated below each tree. For each criterion, groups sited with a same letter on top of boxplot were not statistically different at $\alpha = 0.05$ (LSD test). Till.other: tillage on non-RlmX cultivar residues; Till.RlmX: tillage on RlmX-cultivars residues; MB: Mouldboard ploughing; ref: reference; 2SB: two passages of stubble breaker; 7y: 7-year rotation. Tree figures were realized with the R package ‘rattle’ (Williams, 2011). Darkest box colours correspond to higher group means.

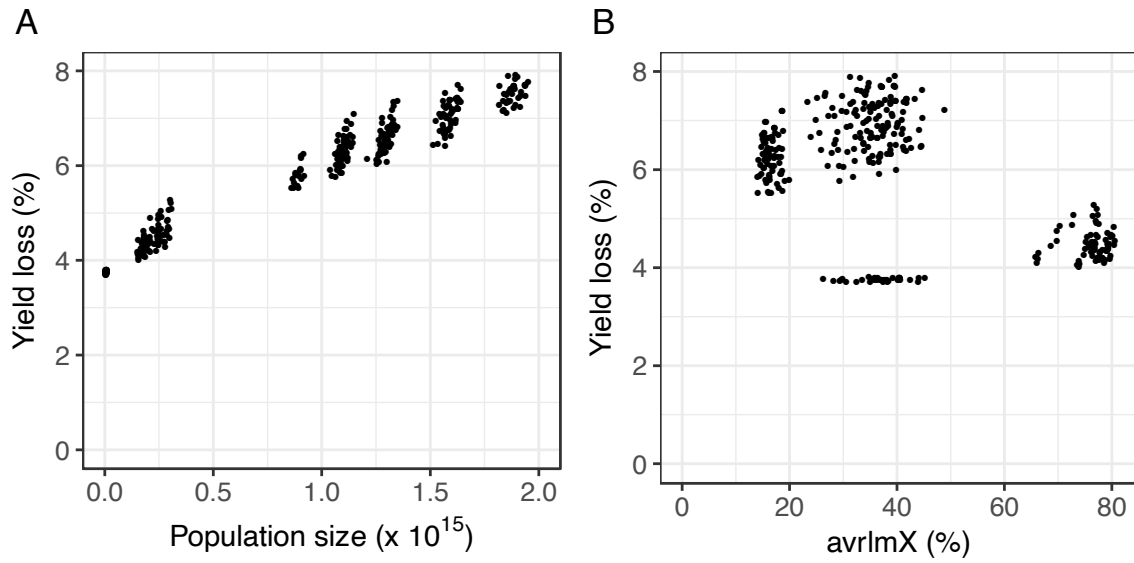


Figure 6. Simulation results for RlmX isolation strategy. Yield losses are plotted against size of the pathogen population (A) and frequency of virulent pathotypes on RlmX-gene (avrlmX, B).

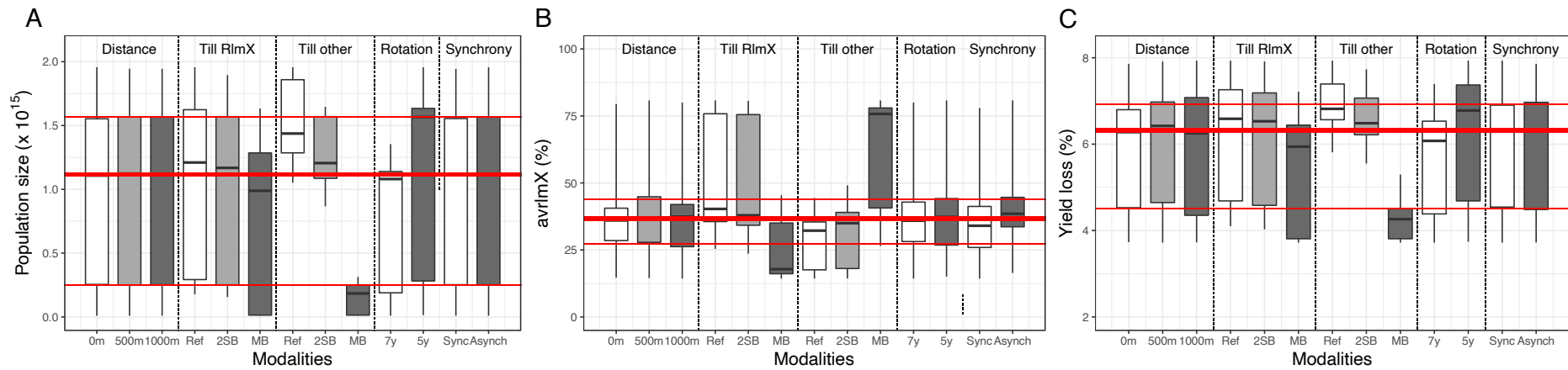


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Extreme values correspond to minimum and maximum simulated values. Red lines indicate the global median (bold line), 25th and 75th quantiles of simulated values for the corresponding variable and isolation strategy. Till. RlmX: tillage on RlmX-cultivars; Till. Other: tillage on non-RlmX cultivars; Ref: reference tillage; 2SB: 2 stubble breakers; MB: Mouldboard ploughing; 7y: 7-year rotation; 5y: 5-year rotation; Synchrony: RlmX-cultivar synchrony; Asynch: RlmX-cultivar asynchrony. Colours of boxplot distinguish the modalities of a factor. Figures were realized with 'ggplot2' R package (Wickham, 2009).

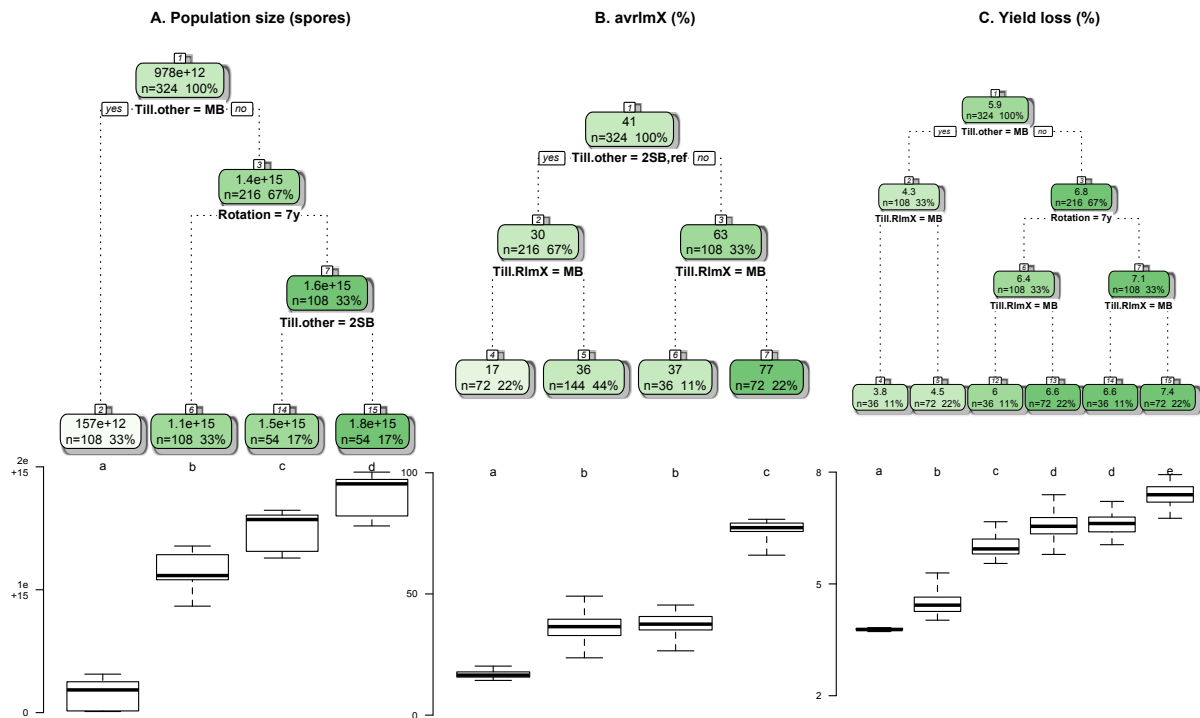


Figure 8. Regression tree models of the three criteria for the RlmX-cultivar isolation strategy: Population size (A), avrlmX (B) and Yield loss (C).

For each group, the 1st number indicates the group mean, the 2nd number (n) indicates the number of simulations, and the 3rd its corresponding percentage. The criterion distribution for each group is indicated below each tree. For each criterion, groups sited with the same letter on top of boxplot were not statistically different at $\alpha = 0.05$ (LSD test). Till.other: tillage on non-RlmX cultivar residues; Till.RlmX: tillage on RlmX-cultivars residues; MB: Mouldboard ploughing; ref: reference; 2SB: two passages of stubble breaker; 7y: 7-year rotation. Tree figures were realized with the R package ‘rattle’ (Williams, 2011). Darkest box colours correspond to higher group means.