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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. Modelbased 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, spatiallyexplicit 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 and the desire to reduce pathogen significance call for the design of disease-buffering or 14 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; Papaïx 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

distance or buffering zones) (e.g., Skelsey *et al.*, 2010 on potato late blight; Colbach *et al.*,
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

scales. Using this type of models in combination with expert knowledge can improve the
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, comparing, and ranking the effectiveness of different types of crop mosaics for phoma stem 113 114 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

The design, assessment, and comparison of strategies combining cropping practices and their
allocation for efficient phoma stem canker control were performed in four steps that combine
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

Our case study was located in the Picardie region (NUTS-2), in northern France. In this
region, an agricultural context (Oise NUTS-3) was defined as corresponding to specific soil
characteristics and cropping systems. Local stakeholders defined cropping systems (Hossard *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
seeds m<sup>-2</sup>, 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 km <sup>2</sup> (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	

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

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 cultivars201 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 1<sup>st</sup> 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).

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

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

and the yield loss due to phoma epidemics (% of potential yield). For each simulated mosaic,
these criteria were averaged over the simulation years, at the landscape scale, in terms of
annual area-weighted values (annual area-weighted sum for population size and annual areaweighted 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 tested using F-tests, and model goodness-of-fit was evaluated by the adjusted R<sup>2</sup> and the error 263 264 size of the residuals (RMSE, Root Mean Square Error). Model residuals were checked for 265 symmetry and normality, and independence from fitted values.

In the second set of analyses, we built regression trees to identify the best performing 266 267 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

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

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

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

293 For WOSR isolation strategy, the WOSR acreage objective was only achieved for the three

replicates of the 7-year rotation of the 0 m isolation distance (i.e., contiguous fields), and it

was associated with low between-year variability (3-9 ha, Table 2). For the 5-year rotation,

the contiguous fields forbidding rule (0 m isolation distance) led to WOSR acreages that were

about 10% lower than the objective (annual average of 301 ha compared to a 334 ha

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

simulation years. Pathogen population size ranged between  $4.5 \times 10^{12}$  spores and  $1.6 \times 10^{15}$ spores; the fraction of virulent pathotypes on RlmX-gene ranged between 9.5% and 81.3%, and yield loss ranged between 1.5% and 7.6%. Yield loss increased with an increase of the pathogen population size, but not with an increase of the fraction of virulent pathotypes on 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 (avrlmX), 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)

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

higher, with the size of the pathogen population ranging between 9.9 x  $10^{12}$  spores and 2 x

 $10^{15}$  spores, the fraction of virulent pathotypes on RlmX-gene ranging between 14% and 81%,

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

always with larger fractions of virulent pathotypes on RlmX gene (Figure 6).

389

390 # Figure 6 approximately here #

391

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

structures promoting large pathogen populations led to lower adaptation potential in theirhost.

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 vield 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

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

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 in a good soil structure (Chan and Heenan, 1996). Although very efficient for burying stubble, 530 531 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-vear 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 local572 pests (e.g., pollen beetle), and farm constraints.

573

574 5. Conclusion

We showed in this study that stubble management was a key practice for phoma control, although displaying opposite results with ploughing of non-RlmX residues leading to lower yield loss and size of the pathogen population, but higher resistance breakdown. Combining intensive stubble management while isolating WOSR source and target fields was even more efficient in controlling the disease, while RlmX-cultivar isolation was not. Large isolation distances between WOSR fields increased phoma control, but did not allow achieving annual 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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600				
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814	Figure	captions
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- Figure 1. Steps for the design and comparison of control strategies
- 816
- 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
- 819 of WOSR fields in year y+1
- 820
- Figure 3. Simulation results for WOSR isolation strategy. Yield losses are plotted against size
- 822 of the pathogen population (A) and frequency of virulent pathotypes on RlmX-gene (avrlmX,
- 823 B).
- 824
- 825 Figure 4. Boxplots of simulated values for Population size (A), Frequency of the virulent
- 826 pathotypes on RlmX-cultivars (B), and Yield loss (C) for the WOSR isolation strategy.
- 827
- 828 Figure 5. Regression tree models of the three evaluation criteria for the WOSR isolation
- 829 strategy: Population size (A), avrlmX (B) and Yield loss (C).
- 830
- 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).
- 834
- 835 Figure 7. Boxplots of simulated values for Population size (A), Frequency of the virulent
- pathotypes on RlmX-cultivars (B), and Yield loss (C) for the RlmX isolation strategy.
- 837
- 838 Figure 8. Regression tree models of the three criteria for the RlmX-cultivar isolation strategy:
- 839 Population size (A), avrlmX (B) and Yield loss (C).
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Strategy	Information	Tillage (on non-RlmX/RlmX fields)	Isolation distance between fields	e WOSR frequency <sup>1</sup>	Temporal synchrony	Replicates	Total
	Number of options	9	3	2	NA	3	162
WOSR isolation		MB/MB; MB/ref; MB/2SB	0 m	14.3%		different	
	Options	ref/ref; ref/MB; ref/2SB	500 m	20%		spatial	
		2SB/2SB; 2SB/MB; 2SB/ref	1000 m			organization	
	Number of options	9	3	2	2	3	324
RlmX		MB/MB; MB/ref; MB/2SB	0 m	14.3%	synchrony	different	
isolation	Options	ref/ref; ref/MB; ref/2SB	500 m	20%	asynchrony	spatial	
		2SB/2SB; 2SB/MB; 2SB/ref	1000 m	1		organization	
					1.0		

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

MB: Mouldboard ploughing; 2SB: 2 passages of stubble breaker; ref: reference tillage; <sup>1</sup>WOSR 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)
		0 m	301±33; 301±51; 301±60	334±5; 334±7; 334±7
5 years	334	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
		0 m	238±9; 243±3; 243±3	236±7; 237±3; 241±1
7 years	239	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

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

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

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

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

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

-: 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.	

		Size of pat population (	hogen spores)	Frequency pathotype gen	y of virulent es on RlmX- ne (%)	Yield lo	oss (%)
Factor	d.f.	MSE	p-value	MSE	p-value	MSE	p-value
Distance	2	7.187 x 10 <sup>26</sup>	0.945	9	0.752	0.300	0.019
Tillage RlmX	2	$2.164 \ge 10^{30}$	< 0.001	24,244	< 0.001	17.294	< 0.001
Tillage Other	1	$5.534 \ge 10^{31}$	< 0.001	41,399	< 0.001	228.273	< 0.001
Rotation	1	$1.024 \ge 10^{31}$	< 0.001	42	0.251	26.904	< 0.001
Synchronism	1	$3.703 \ge 10^{26}$	0.865	1,52	< 0.001	0.008	0.748
Adjusted R <sup>2</sup>		0.969	)	0.	.929	0.9	56
RMSE		1.111 x	$10^{14}$	5.	.544	0.2	.69

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

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 x 10 <sup>32</sup>	82,619.31	450.724
Rotation	$1.375 \ge 10^{31}$	-	30.572
Synchronism	-	-	-
Relative error	0.04	0.04	0.05

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

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



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

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

<sup>2</sup>Stakeholders 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.

<sup>3</sup>Stakeholders 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 (avrlmX, 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), 25<sup>th</sup> and 75<sup>th</sup> quantiles of simulated values for the corresponding variable and isolation strategy. Till. RlmX: tillage on RmX-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 1<sup>st</sup> number indicates the group mean, the 2<sup>nd</sup> number (n) indicates the number of simulations, and the 3<sup>rd</sup> 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).



Figure 7. Boxplots of simulated values for Population size (A), Frequency of the virulent pathotypes on RlmX-cultivars (B), and Yield loss (C) for the RlmX isolation strategy.

Extreme values correspond to minimum and maximum simulated values. Red lines indicate the global median (bold line), 25<sup>th</sup> and 75<sup>th</sup> quantiles of simulated values for the corresponding variable and isolation strategy. Till. RlmX: tillage on RmX-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; Synch: 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 1<sup>st</sup> number indicates the group mean, the 2<sup>nd</sup> number (n) indicates the number of simulations, and the 3<sup>rd</sup> 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.