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Highlights

- Spatial distributions of cropping systems were assessed for their impact on phoma.
- Agronomic and epidemiological criteria were used to characterize phoma control.
- Main explanatory cropping practices differed between the criteria.
- Weather significantly impacted epidemiological criteria of phoma control.
- Sustainable strategies all included a small proportion of RlmX-cultivars.

Meta-modelling of the impacts of regional cropping system scenarios for phoma stem canker control

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1 Abstract

2 In agricultural landscapes, pest and disease control mainly rely on cropping system
3 characteristics and location. We have combined a participatory approach and a spatially-
4 explicit model, to design and assess cropping system scenarios for future contextual changes
5 in the small region of Picardie, France. Phoma stem canker of winter oilseed rape (WOSR), a
6 widespread disease responsible for major economic losses, was used as a case study to
7 investigate the effects of modifying cropping systems, at a regional scale, on disease
8 controlling and on the sustainability of a newly introduced specific resistance gene (RlmX).
9 Meta-models were fitted to assess the effects of cropping practices and weather conditions
10 included in scenarios on three complementary model outputs: size of the pathogen population,
11 yield loss, and fraction of the virulent population on RlmX-cultivars. We ran three replicates
12 of each cropping practice scenario, varying the location of WOSR and associated cropping
13 characteristics within the region. Outputs differed slightly between replicates, but there were
14 no significant differences between replicates ($\alpha=0.001$) for each output. The size of the
15 pathogen population was well explained by winter oilseed rape acreages, cultivar landscape
16 composition and tillage, and the yield loss was explained by weather conditions and cultivars.
17 The fraction of the virulent population on RlmX-cultivars was explained primarily by cultivar
18 landscape composition. These differences in explanatory variables for the different outputs
19 highlighted their complementarity. Cropping practices and weather impacts on the three
20 variables remained consistent among the explored possible future contexts. Highlighting the
21 most efficient cropping practices to be applied in the event of different future changes could
22 help local decision-makers to design cropping practices in the face of contextual change.

23

24

25 1. Introduction

26 In agricultural landscapes, pest and disease control depends on cropping system
27 characteristics. Disease severity is influenced by crop management practices modifying the
28 host (i.e. the crop), the pathogen, or the environment (Krupinsky *et al.*, 2002). Phoma stem
29 canker (causal agent *Leptosphaeria maculans*) of Winter Oilseed Rape (WOSR; *Brassica*
30 *napus*) is an internationally important disease responsible for large economic losses (Fitt *et*
31 *al.*, 2006). Its control currently relies mainly on the use of resistant cultivars, which have
32 quantitative partial resistance, limiting crop damage, and/or qualitative specific resistance,
33 limiting pest attacks. The specific resistance, based on gene-for-gene interaction (Flor, 1971),
34 stops disease development when the crop carries a resistance gene and the pathogen carries
35 the corresponding avirulence gene (Delourme *et al.*, 2006). However, due to widespread use
36 of the same resistance gene, qualitative resistance can be overcome in a few years (Rouxel *et*
37 *al.*, 2003), and requires management to increase the duration of effectiveness. Aubertot *et al.*
38 (2006) showed that preservation of resistance and disease control can be improved by (i)
39 managing pathogen population size (quantitative feature), and (ii) limiting the selection
40 pressure on pathogen populations (qualitative feature). These epidemiological components
41 may be influenced by landscape composition in terms of proportion of host crop (Fitt *et al.*,
42 2006; Skelsey *et al.*, 2010), of cultivars (e.g. on wheat leaf rust epidemics, Papaïx *et al.*, 2011;
43 on virus in Fabre *et al.*, 2012), including resistance gene deployment (Pink and Puddephat,
44 1999), and cropping practices (e.g. on phoma stem canker of oilseed rape, Lo-Pelzer *et al.*,
45 2010). Spatial organisation of WOSR fields during successive years also influences
46 resistance sustainability (e.g. Lo-Pelzer *et al.*, 2010). For phoma stem canker management,
47 the design of control strategies requires scaling up from annual/field to multi-year/regional
48 (Lo-Pelzer *et al.*, 2010). Combining both resistance deployment and cropping practices in
49 space and time may help disease control (Aubertot *et al.*, 2006), since the epidemic cycles of

50 this disease are characterized by year-to-year recurrence processes (Hall, 1992; Lo-Pelzer *et*
51 *al.*, 2009) and long-distance dispersal (5-8 km, Bokor *et al.*, 1975).

52 For phoma stem canker of winter oilseed rape, the main cropping characteristics influencing
53 the disease are cultivar choice (i.e. resistance characteristics; Lo-Pelzer *et al.*, 2009), tillage
54 practices after WOSR harvest (Schneider *et al.*, 2006), fertilization during autumn and sowing
55 dates (Aubertot *et al.*, 2004). Designing sustainable strategies for phoma stem canker control
56 requires these practices to be combined at large spatial and temporal scales (Lo-Pelzer *et al.*,
57 2010). To assess the effects of combinations of practices, the use of a modelling approach
58 integrates all the necessary variables (including cropping system characteristics) at the
59 relevant spatial and temporal scales. It allows virtual experiments to be carried out that would
60 have been impossible in the real world (Legg, 2004). Such experiments evaluate differences
61 in cropping system characteristics, as well as their temporal and spatial locations, for disease
62 control and resistance sustainability. For a complete assessment, all disease characteristics
63 should be evaluated. Disease control and resistance sustainability include different
64 parameters, which may differ between studies (e.g. in Brun *et al.*, 2010; in Fabre *et al.*, 2012).

65 For phoma stem canker, disease development depends on the size of the pathogen population,
66 its genetic structure, and severity (Lo-Pelzer *et al.*, 2009; 2010).

67 Different methods can be used to design strategies at the landscape scale. In the case of
68 agricultural landscapes, decisions about landscape changes and agricultural production are
69 mainly taken by local farmers (Primdahl, 1999) and influenced by stakeholders acting at local
70 and wider scales (e.g. crop collectors; markets). Based on their expertise on local agricultural
71 conditions, stakeholders can envision possible technical changes (Carr and Halvorsen, 2001)
72 in the face of modifications to the local and global context. These locally-decided proposals
73 may be more suitable than generic ones (Brandenburg *et al.*, 1995), as they take into account
74 more complete information (Reed, 2008) on technically-feasible options, constraints,

75 flexibility (Joannon et al, 2006) and cost-effectiveness (Voinov and Bousquet, 2010). To
76 provide useful elements for decision-making on a large spatial scale, a participatory approach
77 can be beneficial, especially when the effective strategies involve the coordination of several
78 stakeholders, including farmers (e.g. on risks from runoff erosion, Souchere *et al.*, 2010).
79 These scenarios may differ among various contexts (Hossard *et al.*, 2013), such as economics
80 (market prices of crops, etc.), which may promote or influence specific crop choices.
81 Designing and assessing strategies of cropping systems with stakeholders may then help to
82 identify reliable and suitable cropping system options that could be used to cope with future
83 contextual changes. The objectives of this paper were to (1) identify scenarios allowing
84 efficient disease control, and (2) assess and rank *ex ante* the impacts of different cropping
85 system scenarios on the control of phoma stem canker on a regional scale.

86

87 2. Materials and methods

88 2.1. Method overview

89 The cropping system scenarios presented in this study are sets of options that could be
90 implemented in the event of future contextual changes, and the scenario ranking was done
91 using regressions to build meta-models. The identification, assessment and ranking of
92 efficient scenarios and cropping practices for phoma control was separated into several steps.
93 (Figure 1):

94 A. Based on the method proposed by Hossard *et al.* (2013), the first step was to design the
95 future contexts and cropping systems that might apply if such changes were to occur. These
96 scenarios were designed with local stakeholders, and defined by a combination of weather
97 patterns and cropping practices. Each cropping practice was described at the regional scale by
98 both the choice of a specific practice (e.g. type of tillage) and its level of adoption (i.e. the
99 extent of this practice in the region).

100 B. In the second step, we ran the collectively-designed scenarios with the spatially explicit
101 numerical model SIPPOM-WOSR (Lo-Pelzer *et al.*, 2010) to assess the effects of the new
102 cropping systems on phoma stem canker control and resistance durability.

103 C. The third step aimed to identify and characterize, for each future context, the cropping
104 system scenarios that enable efficient control of phoma stem canker and/or resistance
105 durability. Scenario outputs were compared to identify those minimizing one evaluation
106 criterion.

107 D. The last step was to identify and rank, for each future context, the cropping characteristics
108 most determinant for phoma control, using linear meta-models.

109 # Figure 1 approximately here #

110 2.2. Study area

111 The Picardie region of northern France was chosen for a case study. A field map was used to
112 support simulations, corresponding to the Beauvais area (Figure 2; 158 arable fields, 16.7
113 km², from 49°25'54.8'' to 49°28'51.2''N and from 02°09'13.0'' to 02°15'13.8''E). Weather
114 data were provided by Meteo France from a weather station located at 49°26'42''N
115 02°07'36''E.

116 2.3. Scenario characteristics

117 In this study, a scenario is composed of detailed cropping practices linked to a contextual
118 change. Scenarios generally include a reference situation and a description of driving forces
119 for the future (Alcamo and Henrichs, 2008). Therefore local stakeholders first designed
120 reference situations. Three reference situations of cropping systems were characterized, each
121 corresponding to an agronomically uniform sub-region (Table 1). The stakeholders then
122 imagined possible contextual changes (called futures), which would imply modifications in
123 cropping practices (see Hossard *et al.* (2013) for details). Three types of scenario were
124 designed: policy scenarios, environmental scenarios and economic scenarios. Policy scenarios

125 were possible future contexts in which policies would be changed. Two types of policy were
126 considered: the banning of autumn organic manuring of WOSR, and the exclusion of cultivar
127 types from the market, obliging farmers to grow a single type of cultivar (defined by its
128 resistance type - qualitative or quantitative - and its level of quantitative resistance).
129 The environmental scenarios supposed weed issues in WOSR that would require mitigation
130 through changes in the crop sequence and increase the return time of WOSR. Environmental
131 scenarios thus pointed to a decrease in the frequency of WOSR on a regional scale. Economic
132 scenarios indicated a competitive advantage of WOSR over other crops due to its price,
133 prompting an increase in the surface area of WOSR. Policy scenarios were applied to each of
134 the three sub-regions. Environmental scenarios were applied to Tardenois, and economic
135 scenarios were applied to Oise and Somme (Table 1).

136 # Table 1 approximately here #

137 Stakeholders described the possible modifications of cropping practices for each specific
138 future (Table 1). They suggested two weather options: the current weather and one with
139 greater extremes, such as warm wet autumns, *a priori* favourable to phoma development.
140 Each combination of cropping characteristics and weather pattern defined a scenario to be
141 simulated with the SIPPOM-WOSR model. The number of scenarios differed between futures
142 due to the number of tested cropping practices and their options (Table 1). Three replicates of
143 each scenario were performed, varying in the location of WOSR and associated cropping
144 characteristics within the region, since no specific rule for crop or practice location was
145 suggested by stakeholders (Figure 2). For each WOSR frequency, corresponding crop
146 rotations were applied to fields, e.g. for a WOSR frequency of 50%, each field was cropped
147 with WOSR one year out of two. WOSR frequencies were deduced from crop rotations
148 designed by stakeholders. Autumn fungicide and organic nitrogen applications were defined
149 as a fraction of WOSR areas with application. Fungicides were applied on October 20th (as

150 now) at the current rate; nitrogen fertilizers were applied at sowing, using 80 kg of nitrogen
151 per hectare, as indicated by stakeholders. For each future, stakeholders designed each
152 cropping practice independently from each other.

153 Cropping practices are necessary inputs for SIPPOM-WOSR simulations, i.e. specification
154 (value) for seven variables, defined yearly at field and/or at regional scale: WOSR acreages,
155 sowing dates, sowing densities, cultivars, nitrogen fertilization at sowing, autumn fungicide
156 application and tillage after WOSR harvest. Cropping practices were applied to all fields,
157 according to their frequency at the regional scale (Table 1).

158 # Table 2 approximately here #

159 # Figure 2 approximately here #

160

161 2.4. Model-based scenario simulation

162 2.4.1. Model description

163 SIPPOM-WOSR is a spatially-explicit model simulating the effects of spatially-distributed
164 cropping systems on phoma stem canker. It integrates epidemiological, population and crop
165 model approaches to simulate the evolution of *L. maculans* under considered cropping
166 systems (see Lô-Pelzer *et al.* (2010) for details). The model inputs include the field plan of the
167 considered region (field locations and related soil characteristics), local weather data (daily
168 rainfall, temperature, wind direction and intensity, wetness duration, evapotranspiration and
169 radiation), the genetic structure of the initial pathogen population (i.e. frequency of the
170 considered avirulent genes) and its location (linked with WOSR-field locations in the
171 initialization simulation year), the spatially distributed cropping systems (annual location of
172 WOSR fields and applied cultivation techniques, i.e. sowing time and density, cultivar,
173 autumn nitrogen fertilization, fungicide application, harvest time, tillage operation after
174 WOSR harvest and sowing date of the next crop). These input variables influence the annual

175 life cycle of the pathogen, *Leptosphaeria maculans*, and WOSR crop growth through five sub-
176 models: primary inoculum production, pathogen dispersal, pathogen genetic evolution, crop
177 growth, and crop infection and yield loss. Model outputs are annual yield loss (due to phoma
178 stem canker), pathogen population structure, and size defined at field and field map scales.

179 2.4.2. Scenario simulations

180 Each scenario was simulated with SIPPOM-WOSR for five years (one year of initialization
181 and four years of simulation *per se*). In all scenarios, the location of WOSR fields differed
182 each year according to crop rotations (WOSR frequency). Scenarios were evaluated using
183 three evaluation criteria: the fraction of virulent pathotypes on the studied specific gene
184 (RlmX-gene) introduced into the landscape (i.e. variable avrlmX), the size of the pathogen
185 population (i.e. variable Pop_{size}) and the yield loss (i.e. variable Y_{loss}) due to phoma stem
186 canker epidemics. These criteria were considered for the last simulated year. The evaluation
187 variables were characterized for each scenario at the landscape scale: area-weighted values
188 averaged at landscape scale were used for variables avrlmX and Y_{loss} and the area-weighted
189 values sum was used for Pop_{size}, i.e. individual field output was weighted by field size.

190

191 2.5. Analyses of scenario performance

192 2.5.1. Preliminary analyses

193 Scenarios were analysed by sub-regions and futures, since each future represented possible
194 responses to a specific contextual change. We considered six cases: ‘policy’ scenarios for the
195 sub-regions Tardenois, Somme, and Oise (3 cases); ‘environmental’ scenarios for the sub-
196 region, Tardenois (1 case); and ‘economic’ scenarios for the sub-regions, Somme and Oise (2
197 cases).

198 To represent qualitative and quantitative resistance on evaluation criteria, two indicators were
199 averaged at the regional scale: the frequency of RlmX-cultivars (in % of cropped WOSR) and

200 a synthetic indicator describing quantitative resistance (Quantitative Resistance level, or QR
201 level). For each scenario, QR level was calculated as:

$$202 \text{ QR_lev}_i = \sum_{j=1}^n a_j \cdot C_{vij} \text{ (Equation 1)}$$

203 QR_lev_i is the level of quantitative resistance calculated for scenario i , j is the cultivar type
204 ($j=1 \dots 3$), a_j is the parameter characterizing the level of quantitative resistance for each
205 cultivar j and C_{vij} is the proportion of cultivar j in scenario i . There are three types of cultivar:
206 sensitive cultivars ($a_j=0$), cultivars with medium QR level ($a_j=1$), and cultivars with high QR
207 level ($a_j=2$). This indicator thus ranges between 0 and 2. Levels of quantitative resistance were
208 determined by local stakeholders; they assigned a medium QR level to all cultivars with the
209 RlmX-gene.

210 To verify the appropriateness of (1) considering the three random replicates in a single
211 analysis and (2) considering the three evaluation criteria (Pop_{size} , Y_{loss} and avrImX), Pearson
212 and Spearman correlation tests were performed for each future and each sub-region. First we
213 ran the tests between replicates for each criterion, and then between criteria, considering the
214 three scenario replicates together.

215 2.5.2. Identification of efficient scenarios

216 For each future, the yield loss, size of pathogen population and frequency of virulent
217 pathotypes were analysed to identify and characterize the most efficient cropping practices for
218 each contextual change. For each future and sub-region, three scenarios were chosen, each to
219 minimize one of the three evaluation criteria. The three replicates of each scenario and the
220 reference situation were illustrated with a spider diagram to evaluate a trade-off of phoma
221 control. The cropping practices corresponding to these scenarios were indicated in another
222 spider diagram to allow comparison between efficient scenarios (i.e. efficient cropping
223 practice combinations).

224 2.5.3. Identification of efficient techniques with the three evaluation criteria using meta-
225 models

226 We developed linear mixed models to test the effects of cropping practices on the three
227 evaluation criteria for each future and sub-region. For the complete models, we included and
228 tested eight possible explanatory variables: frequency of WOSR in the landscape (as % of
229 cropped area), sowing date (current vs. early), sowing density (in seeds.m⁻²), percentage of
230 WOSR-areas with organic nitrogen fertilization (as % of cropped WOSR where a rate of 80
231 kgN.ha⁻¹ is applied), frequency of RlmX-cultivars (as % of cropped WOSR), level of
232 quantitative resistance (QR, see Equation 1 above), tillage practices (number of operations),
233 and use of fungicide (as % of cropped WOSR, current product and rate of application) (Table
234 1). The weather effect (current vs. weather with wet and warm autumns; Table 1) was
235 described using an additive random effect only, since farmers cannot control this variable.

236 Each cropping practice was analysed independently and no interactions were included
237 because stakeholders designed cropping practices that were independent of each other (and of
238 weather). This suggests that farmers would manage the tested cropping practices
239 independently.

240 The three response variables were avrlmX, Pop_{size} and Y_{loss}. Before carrying out regressions,
241 we chose explanatory variables that only included the cropping practices to be tested in the
242 future concerned (Table 1) and excluded correlated ones. The only correlated variables were
243 the level of quantitative resistance and the frequency of RlmX-cultivars (p<0.001). For each
244 future, we selected the better of these two explanatory variables for the final model: frequency
245 of RlmX-cultivars for the output variable avrlmX and level of quantitative resistance for
246 Pop_{size} and Y_{loss}. Different regression models were developed for each future, sub-region and
247 evaluation criterion:

248 $Pop_size_{ijk} = a_{0k} + a_1.F_WOSR_{ij} + a_2.Sow_Date_{ij} + a_3.Sow_Density_{ij} + a_4.N_org_{ij} + a_5.QR_lev_{ij}$
 249 $+ a_6.Tillage_{ij} + a_7.Fungi_{ij} + \epsilon_{ij}$, with $\epsilon_{ij} \sim N(0, \tau^2)$ and $a_{0k} \sim N(a_0, \sigma_0^2)$ (Equation 2)

250 $avrlmX_{ijk} = a_{0k} \cdot (1 - \exp(a_1.F_WOSR_{ij} + a_2.Sow_Date_{ij} + a_3.Sow_Density_{ij} + a_4.N_org_{ij}$
 251 $+ a_5.F_RlmX_{ij} + a_6.Tillage_{ij} + a_7.Fungi_{ij} + a_8)) + \epsilon_{ij}$, with $\epsilon_{ij} \sim N(0, \tau^2)$ and $a_{0k} \sim N(a_0, \sigma_0^2)$
 252 (Equation 3)

253 where Pop_size_{ijk} is the size of the pathogen population summed over fields at the end of the
 254 simulation (spores) in the i^{th} ($i=1 \dots 3$) replicate of the j^{th} scenario for the k^{th} weather ($k=0$ for
 255 current and $k=1$ for weather with warm and wet autumns), $avrlmX_{ijk}$ is the fraction of virulent
 256 pathotypes on the RlmX-gene in the i^{th} replicate of the j^{th} scenario for the k^{th} weather, a_{0k} is
 257 the mean size of the pathogen population in model (2) and the mean fraction of virulent
 258 pathotypes on RlmX-gene in models (3) for the weather k , $a_1 \dots a_8$ are the mean effects of the
 259 eight explanatory variables, and ϵ_{ij} is the residual error term. F_WOSR_{ij} is the frequency of
 260 WOSR in the landscape (% of cropped area), Sow_Date_{ij} is the sowing date (0 for current and
 261 1 for early sowing, unitless), $Sow_Density_{ij}$ is the sowing density in seeds.m⁻², N_org_{ij} is the
 262 fraction of WOSR with autumn organic nitrogen application (% of WOSR areas), QR_lev_{ij} is
 263 the level of quantitative resistance (continuous, unitless), F_RlmX_{ij} is the fraction of WOSR
 264 cropped with RlmX-cultivars (% of WOSR area), $Tillage_{ij}$ is the number of tillage operations
 265 (discontinuous), and $Fungi_{ij}$ is the fraction of WOSR with fungicide applications (% of
 266 WOSR areas).

267 All equations included a log-transformed output variable (evaluation criterion). The log-
 268 transformation was chosen since it retains the units of the analysed variable. Only the best
 269 models are presented.

270 Models (2-3) were compared for each criterion separately, based on the Akaike information
 271 criterion (AIC). Only significant explanatory variables ($\alpha = 0.001$) were kept in the
 272 models. For each evaluation criterion, these models were also compared to a constant model

273 without explanatory variables and random effects. The distributions of the residuals of the
274 models showing the lowest AIC were symmetrical and did not show any trend. The models
275 showing the lowest AIC were selected to analyse the effects of the cropping system scenario
276 on the evaluation criteria. Only the models with the lowest AIC are presented here.
277 Determination coefficients (R^2) were calculated to characterize the best models (i.e. with the
278 lowest AIC). We used the method proposed by Nakagawa and Schielzeth (2013) for mixed-
279 models. For each model, two determination coefficients were calculated: marginal R^2 is the
280 variance explained by only the fixed factors; conditional R^2 is the variance explained by the
281 fixed and the random effects.

282 2.5.4. Statistical analysis

283 All analyses were performed with the R software (R Development Core Team, 2013). Spider
284 diagrams were developed using the R package “fmsb” (Nakasawa, 2010). The regression
285 models were fitted with the function lme and nlme of the R package “nlme” for the linear and
286 the exponential models respectively (Pinheiro *et al.*, 2013).

287

288 3. Results

289 3.1. Reference and future simulations' results

290 Simulations of reference situations and future scenarios gave very different values for the
291 three evaluation criteria, i.e. yield loss (Y_{loss}), size of the pathogen population (Pop_{size}) and
292 frequency of virulent pathotypes on RlmX-cultivars (avrlmX) (Figure 3).

293 In the reference situations, yield loss was about twice as high for the sub-region Somme
294 (18.4% on average for the three replicates) and about the same for Oise and Tardenois (means
295 9.2 and 9.7% respectively) (Figure 3A1); avrlmX was smaller for Somme (mean 32%) and
296 similar for Oise and Tardenois (51.4 and 47.5% respectively) (Figure 3A2). The reference
297 sizes of pathogen populations differed; reference situations for Somme led to the largest

298 Pop_{size} (2.6×10^{15} spores on average) as compared to Tardenois (2×10^{15} spores) and Oise (1.2
299 $\times 10^{15}$ spores) (Figure 3A1). Simulated yield loss in the reference situation did not differ
300 between replicates (i.e. spatial allocations, see Figure 1) for the three sub-regions. Oise and
301 Tardenois had similar simulated avrlmX; it was smaller for Somme. Simulated references
302 were more diverse for the size of the pathogen population in the three sub-regions, with
303 standard deviations of 1.4×10^{14} spores in Oise and 1.7×10^{14} in Tardenois and Somme sub-
304 regions (Figure 3A1).

305 In the policy scenarios, the range of simulated yield loss was similar in all sub-regions (2-
306 44%, 3-51% and 4-50% of virulent pathotypes for Oise, Somme and Tardenois respectively);
307 simulated Y_{loss} were mainly higher than the reference (Figure 3B1). The simulated sizes of
308 pathogen populations were lower for the sub-region Oise ($1-2.2 \times 10^{15}$ spores) than for the two
309 other sub-regions ($1.8-3.9$ and $1.9-4 \times 10^{15}$ spores for Somme and Tardenois respectively). For
310 Somme and Tardenois, policy scenarios mainly led to higher Pops_{size} compared to reference
311 situations (Figure 3B1). The simulated avrlmX ranged between almost 0 % ($10^{-5}\%$) and 100%
312 of virulent pathotypes for the three subregions, corresponding to scenarios with 0 and 100%
313 of cropped RlmX-cultivars respectively (data not shown). In scenarios using reference
314 cultivars (Table 1), simulated avrlmX were closer to the reference situations. For Somme sub-
315 region (6% of RlmX-cultivars), avrlmX ranged between 26 and 39%. For Oise and Tardenois
316 (15% of RlmX cultivars), simulated avrlmX were higher (36-53% and 39-51% respectively)
317 (Figure 3B2).

318 In the sub-region Tardenois, simulation of environmental scenarios mainly outperformed
319 reference situations for simulated Pop_{size} ($0.48-2.93 \times 10^{15}$ spores, with 88% of scenarios lower
320 than reference Pop_{size}) (Figure 3A1). Yield loss varied between 2 and 20%. All simulated
321 pathotypes were virulent on RlmX-cultivars (avrlmX) for scenarios where only RlmX-
322 cultivars were grown. Simulated avrlmX decreased for scenarios with fewer RlmX-cultivars:

323 avrlmX ranged between 94-95% for 60% of RlmX-cultivars; between 80-95% for 40% of
324 RlmX-cultivars and 33-56% for 15% of RlmX-cultivars (reference cultivar configuration,
325 Table 1) (Figure 3A2).

326 In the economic scenarios, simulated yield loss was always lower than the reference for the
327 Somme sub-region (Figure 3A1). They were also lower than the reference for Oise sub-
328 region, except for scenarios with 0% of RlmX-cultivars and 40% of cultivars with medium
329 quantitative resistance (Figure 3A2). Simulated Pop_{size} were mainly larger than the reference
330 situations for both sub-regions (Figure 3A1); simulated avrlmX were mostly lower than the
331 reference (Figure 3A2). The simulated Pop_{size} and Y_{loss} were lower for Oise than for Somme
332 for the economical scenarios, but not the virulent pathotypes on RlmX-cultivars (Figure 3A).

333 # Figure 3 approximately here #

334 3.2. Scenarios minimizing phoma evaluation criteria

335 In the different futures, the three evaluation criteria of phoma control (Y_{loss} , Pop_{size} and
336 avrlmX) were rarely minimized by the same combinations of cropping practices. Moreover,
337 scenarios minimizing one evaluation criterion may not be efficient for another (Figures 4 and
338 5). These results are consistent with those of correlation tests. Pearson correlations indicated a
339 relative independence between Pop_{size} and avrlmX, with either non-significant correlations
340 ($\alpha = 0.05$) or very low coefficients of determination ($R^2 < 0.08$) (Appendix A).

341 Correlations were also low between Y_{loss} and avrlmX ($R^2 < 0.22$). Only correlations between
342 Pop_{size} and Y_{loss} were consistently significant ($\alpha = 0.001$), with high determination
343 coefficients for policy scenarios (0.69-0.77) and lower ones for environmental and economic
344 scenarios (R^2 between 0.19-0.22) (Appendix A).

345 Two diagrams were drawn for each future and sub-region to compare and illustrate
346 minimization scenarios. The first illustrates cropping practices for the three scenarios; the
347 second shows the three evaluation criteria for the three scenarios. Maximum values are at the

348 edges of the diagrams; minimum values are at the center of the spider diagram. We included
349 zero values for the evaluation criteria and for quantitatively described cropping practices.
350 Current weather is at the centre of the diagram and the option with warm wet autumns at the
351 edge. Current sowing dates are at the centre of the diagram. Minimum and maximum values
352 for diagrams were determined by considering the reference situation and all scenarios of the
353 future concerned for each sub-region.

354 For policy future scenarios, cropping practice combinations and their effects on phoma
355 control differed within and between sub-regions for most evaluation criteria minimization;
356 however, these differences could be very small (e.g. in Tardenois, with a difference of 0.24%
357 Y_{loss} between scenarios minimizing avrlmX and Y_{loss} respectively; see orange and green
358 scenarios of Tardenois in Figure 4). For the Somme sub-region, scenarios minimizing
359 individual evaluation criteria performed well for the other criteria. These scenarios
360 incorporated common cropping practices (high use of nitrogen fertilization, no use of RlmX-
361 cultivars, and a high level of quantitative resistance) and only differed in their sowing date.
362 Early sowing (1 week before current practices) minimized Pop_{size} and avrlmX but not Y_{loss}
363 (Somme in Figure 4). For the Tardenois sub-region, only scenarios minimizing avrlmX
364 performed well for Y_{loss} and Pop_{size} ; Y_{loss} and Pop_{size} minimization scenarios both led to
365 high avrlmX (Tardenois in Figure 4). For the Oise sub-region, only the scenarios minimizing
366 Pop_{size} performed poorly on the two other criteria (Oise in Figure 4). For Oise and Tardenois,
367 best phoma control scenarios included high organic fertilization, current sowing dates, low
368 RlmX-cultivar frequency, and a high level of quantitative resistance (Figure 4).

369 # Figure 4 approximately here #

370 In the environmental scenarios, single-criterion minimization scenarios always performed
371 well on the other two criteria. They all included small areas with WOSR (10%), an increased
372 tillage intensity and a high level of quantitative resistance, involving a low use of RlmX-

373 cultivars. Simulated avrlmX was lowered with early sowing; Y_{loss} and avrlmX were decreased
374 by decreasing sowing density (Tardenois in Figure 5).

375 In the economic scenarios, those minimizing Y_{loss} and Pop_{size} performed similarly for the three
376 criteria in the Somme and Oise sub-regions, but corresponded to highest avrlmX in Oise
377 (Figure 5). In Oise, scenarios minimizing avrlmX corresponded to highest Pop_{size} and Y_{loss} .

378 Similarly, some cropping practices maximizing phoma control differed between Somme and
379 Oise. Pop_{size} and Y_{loss} were minimized by a low cropping of WOSR (15%); avrlmX was
380 minimized by a medium cropping of WOSR (20%) in both sub-regions (Somme and Oise in
381 Figure 5). For the Oise sub-region, avrlmX was minimized when no RlmX-cultivar was
382 grown; but Y_{loss} and Pop_{size} were minimized at 15% or RlmX-cultivars. This was not the
383 case for the Somme sub-region, where all criteria were minimized without RlmX-cultivars.
384 All minimization scenarios for economic scenarios included high use of fungicide (Somme
385 and Oise in Figure 5).

386 Almost all scenarios minimizing evaluation criteria contained the weather option of warm wet
387 autumns (Figures 4 and 5), with the same cropping practices as for the current weather, so the
388 same combinations of practices minimized the considered criteria for both weather options
389 (data not shown).

390 # Figure 5 approximately here #

391 3.3. Scenario replicates

392 For each scenario of each future, the three scenario replicates (i.e. spatial allocation, Figure 2)
393 minimizing one evaluation criterion were very close with regards to the other criteria; i.e. the
394 three replicates of the scenario minimizing Y_{loss} ranked similarly for Pop_{size} and avrlmX
395 (Figures 4 and 5), with one exception. In the Oise sub-region and for the economic future, the
396 replicates minimizing the size of the pathogen population differed for both Y_{loss} (2-5%) and
397 avrlmX (37-62%) (Oise, Figure 5). However, there were no significant differences between

398 replicates ($\alpha=0.001$) for each evaluation criterion, sub-region or future. All regression
399 models analysing the effects of cropping practices on evaluation criteria provided
400 determination coefficients larger than 0.83, except for the size of the pathogen population for
401 economic scenarios in the sub-region Oise ($R^2=0.62$) (Appendix B).

402 3.4. Effect of cropping system characteristics on phoma control

403 The best models were obtained with linear regressions for Y_{loss} , Pop_{size} ; and avrlmX in futures
404 where only two values for RlmX -cultivars were tested (economic scenarios). In
405 environmental and policy scenarios, avrlmX was best modelled with exponential models
406 (Appendix C & D). The main explanatory cropping practices differed between the three
407 evaluation criteria (Table 2).

408 In all futures, scenarios with the warm wet autumn weather option had lower Y_{loss} and Pop_{size} ,
409 and showed a significant effect of weather on the mixed models' intercept (Table 2; Appendix
410 C). The variance associated with weather (partial r^2) differed between futures and criteria
411 (Figure 6).

412 Simulated avrlmX was mostly explained by the fraction of RlmX -cultivars grown (Figure 6).
413 Increasing this proportion by 1% increased $\log(\text{avrlmX})$ by 0.6 to 2.5% depending on future
414 and sub-region (Table 2). The effect of WOSR area on avrlmX was significant ($\alpha=0.001$)
415 in environmental and economic futures but minimal in the model (partial determination
416 coefficients between 4.10^{-5} and 3.10^{-3}). Its effect on avrlmX was not always positive (Table
417 2).

418 WOSR area impacted simulated Pop_{size} primarily in the environmental and economic futures
419 (Figure 6); an increase of 1% in WOSR area increased the logarithm of the size of the
420 pathogen population of about $5-7 \times 10^{13}$ spores (Table 2). The effect of WOSR fraction on
421 yield loss was lower. Y_{loss} and Pop_{size} , especially the former, depended heavily on the level of
422 quantitative resistance, especially for policy scenarios (Table 2). In policy scenarios, the

423 increase in area with nitrogen fertilization decreased Pop_{size} and Y_{loss} in Tardenois and
424 Somme; in Oise, sowing one week before current practice increased these two evaluation
425 criteria (Table 2). In environmental scenarios, $\log(\text{Pop}_{\text{size}})$ decreased by 5×10^{14} spores and
426 $\log(Y_{\text{loss}})$ decreased by 0.25% (Table 2).

427 # Figure 6 approximately here #

428 # Table 2 approximately here #

429 4. Discussion

430 This study analysed and compared possible future scenarios in different sub-regions. Our
431 analyses highlighted (1) the impact of potential future cropping systems on phoma control; (2)
432 the factors influencing the disease in the event of these cropping changes; and (3) efficient
433 combinations of practices for phoma control, differing between futures and sub-regions. We
434 used spider diagrams and regression models to highlight the main control levers and how they
435 would differ between futures and sub-regions.

436 In this study, we have shown that the three evaluation criteria (two epidemiological and one
437 agro-economic) were not redundant: minimizing one of them could adversely affect another.
438 The minimization of each criterion was the product of different combinations of cropping
439 practices, as their main driving cropping practices differed (Figures 4-6, Table 2). Often,
440 sustainability of resistant cultivars is assessed by focusing on the evolution of the frequency
441 of virulent pathotypes on a specific gene within the pathogen population, i.e. the time between
442 its introduction and the time when it reaches a given threshold (e.g. Brun *et al.*, 2010). Such
443 thresholds are usually ‘randomly’ determined for scenario comparison, but not to define
444 technical solutions to satisfy farmers’ objectives. Farmers are more sensitive to disease effects
445 on yield (Savary *et al.*, 2006) than on epidemiological mechanisms. Finally, for disease risk
446 evaluation, the size of the pathogen population was also studied to show the disease pressure
447 (Lo-Pelzer *et al.*, 2010) or the regional density of inoculum (Plantegenest *et al.*, 2007;

448 Aubertot *et al.*, 2006), together with complete information on frequency of virulent
449 pathotypes on a gene (Brun *et al.*, 2010). These three indicators provide complementary
450 information. First, one indicator could balance another. Population size could indeed balance
451 the frequency of virulent pathotypes, e.g. a high population with a low RlmX-pathotype
452 frequency could mean higher RlmX pathogens than a low population with high RlmX-
453 pathotype frequency. Secondly, they are of particular interest to different stakeholders: whilst
454 a breeder might be more concerned with the evolution of the pathogen population's
455 resistance, farmers would be more concerned with yield loss.

456 When cropped cultivars were tested, the frequency of virulent pathotypes on the RlmX-gene
457 was mainly determined by RlmX-cultivars. This is in agreement with previous studies
458 (surveys in Rouxel *et al.*, 2003; model-based studies in van den Bosch and Gilligan, 2003;
459 Fabre *et al.*, 2012; statistical analyses in Papaix *et al.*, 2011). On the other hand, the overall
460 level of quantitative resistance impacted the yield loss and the size of the pathogen
461 population. Such a large effect on the size of the pathogen population is consistent with
462 previous findings: quantitative resistance decreases internal stem canker severity (Huang *et al.*
463 *et al.*, 2009), which in turn is responsible for a decrease in primary inoculum production (Lo-
464 Pelzer *et al.*, 2009). Cropping practices leading to best phoma stem canker control all included
465 a small proportion of RlmX-cultivars. This is partly due to the moderate level of quantitative
466 resistance associated by stakeholders with RlmX-cultivars, which is lower than the high level
467 of quantitative resistance of other tested cultivars. This hypothesis should be confirmed,
468 although the level of quantitative resistance remains hard to assess (Huang *et al.*, 2014), as is
469 its potential erosion (Andrivon *et al.*, 2007).

470 As expected, important drivers of population size also included positive effects of WOSR
471 acreage (e.g. Fitt *et al.*, 2006) and tillage intensity (e.g. Schneider *et al.*, 2006). Other
472 practices included in the model and modified by stakeholders had smaller effects (although

473 sometimes significant) on the assessment criteria: for instance increased autumn nitrogen
474 fertilization significantly decreased yield loss for the three sub-regions (Table 2). These
475 results differ from those of other studies (e.g. Aubertot *et al.*, 2004) but are consistent with the
476 stakeholders' views. Moreover, the rates of nitrogen used in the cited study are very high (250
477 kgN.ha⁻¹; Aubertot *et al.*, 2004) as compared to current rates (here 80 kgN.ha⁻¹).

478 The impact of warm wet weather was usually significantly negative, but its importance
479 depended on cropping practices tested (Table 2). The effect of warm wet autumns reduced
480 yields more than it reduced spore numbers, whose main drivers were either the positive effect
481 of the WOSR area or cultivar type. Using a weather dataset likely to present favourable
482 conditions for phoma stem canker development decreased yield loss and the size of the
483 pathogen population in all futures. Salam *et al.* (2011) find similar effects of climate on
484 blackspot in field peas. This could be linked with the model behaviour: with the temperature
485 being higher, rape plants would grow faster, reaching the 6-leaf stage earlier in the season
486 (when plants become highly resistant to primary inoculum, whatever the cultivar; Brunin and
487 Lacoste, 1970). Thus the time for pathogen dispersal to be successful in infecting plants
488 would be reduced, and in the event of global warming, this might decrease the risk from
489 phoma. Weather has also been found to modify disease incidence in other pathosystems. For
490 grapevine moth and powdery mildew, Caffarra *et al.* (2012) find that an increase of
491 temperature has a detrimental effect on crop yield. However, this is due to the temperature
492 effects on the asynchrony of pathogen and crop resistance (Caffara *et al.*, 2012). Similarly, in
493 the case of potato late blight, Skelsey *et al.* (2010) show the impact of weather on the
494 coincidence in time and space of the pathogen and the crop susceptibility stage. Skelsey *et al.*
495 (2010) find different effects of management strategies according to meteorological conditions,
496 e.g. direction of spore dispersal by wind. In our study, stakeholders tested weather condition

497 changes for all futures. Thus, climate change was not, in that sense, the driver for practice
498 changes, as might have been expected (e.g. Rounsevell *et al.*, 2005).

499 We also showed that the control of phoma depended strongly on both the regional context
500 (reference situations) and the designed futures and consequent levers (Figure 3). Thus our
501 results, based on model simulations, are dependent on both region and context. Future
502 scenarios were built to explore possible cropping systems that could influence the control of
503 phoma stem canker in a specific context. The resulting scenarios and possible cropping
504 systems could help in future cropping decisions (e.g. what cropping practices to avoid or
505 promote). Scenario analyses resulted in meta-models, which highlighted specific levers for
506 each future. Meta-models can be very useful because they synthesize complex models into
507 models that become clearer (Colbach, 2010) and can help with the assessment of new
508 scenarios without requiring new model simulation (within the validity domain of the meta-
509 model). Meta-models can help decision-making because they help explain the main levers,
510 although the testing of new scenarios should be limited to initially-tested variables (e.g. in the
511 range of initially tested cropping practices) and parameters (e.g. field map, weather). To be
512 relevant, meta-models should be based on *in silico* scenario design, and explore the most
513 significant variables, in a realistic range. This can be ensured by involving stakeholders in
514 scenario design, instead of researchers (e.g. Colbach *et al.*, 2010; Lautenbach *et al.*, 2009;
515 Wechsung *et al.*, 2000) or by simulation (e.g. Tricault *et al.*, 2009, Bergez *et al.*, 2010). The
516 more generic scenarios could remain theoretical: (1) their in-field local feasibility could not
517 have been assessed, but by contrast it is a ‘given constraint’ in a participatory approach (e.g.
518 Anderson *et al.*, 1998); (2) drivers of cropping system change could not have been highlighted
519 (i.e. local priorities; Dougill *et al.*, 2006); (3) cost-effectiveness of such changes may have
520 been poorly estimated as compared to their direct assessment by stakeholders (e.g. Voinov
521 and Bousquet, 2010).

522 In this study, we aggregated individual field simulation outputs partly resulting from between-
523 field interactions (i.e. phoma wind-dispersal). This may explain the different impacts of the
524 areas cropped with WOSR on the evolution of RlmX-virulent pathotypes (positive and
525 negative impact in the environmental and economic futures respectively (Table 2)). This
526 could be due to the distances between compatible emitting and receiving fields. Although
527 these distances may vary between spatial replicates, they will be smaller when a large area of
528 WOSR is cropped with RlmX-cultivars: the higher the fraction of WOSR with RlmX-
529 cultivars, the higher the probability for a target (receiving) field to be adjacent to a compatible
530 emitting field. These results suggest that detailed characterization of cultivar's locations would
531 be necessary in order to design strategies for sustainable use of newly released sustainable
532 cultivars, and assess the effects of landscape structure on pathogen dispersal and evolution
533 (e.g. Plantegenest *et al.*, 2007). Additional variables for scenario analyses could include the
534 areas, orientations, and distances between emitting and receiving fields (e.g. Colbach *et al.*,
535 2005). Characterizing the local diversity and the possible aggregation (e.g. Viaud *et al.*, 2008)
536 in terms of cultivar composition could improve scenario assessment with regard to resistance
537 sustainability.

538 In conclusion, this study provides insight into cropping system effects on a current disease
539 epidemic for possible futures. Application of meta-models to analyse simulation outputs of
540 collaboratively-built scenarios revealed the need to consider different assessment criteria for
541 phoma stem canker control. These criteria were not determined by the same cropping
542 practices and/or weather patterns, and may each correspond to a factor that requires
543 management (yield loss for farmers and cooperatives/retailers; resistance sustainability for
544 plant breeders). Highlighting the most efficient cropping practices (e.g. WOSR return delay;
545 cultivar) to be applied in the event of different future changes could help local decision-
546 makers to design cropping practices to cope with contextual change.

547

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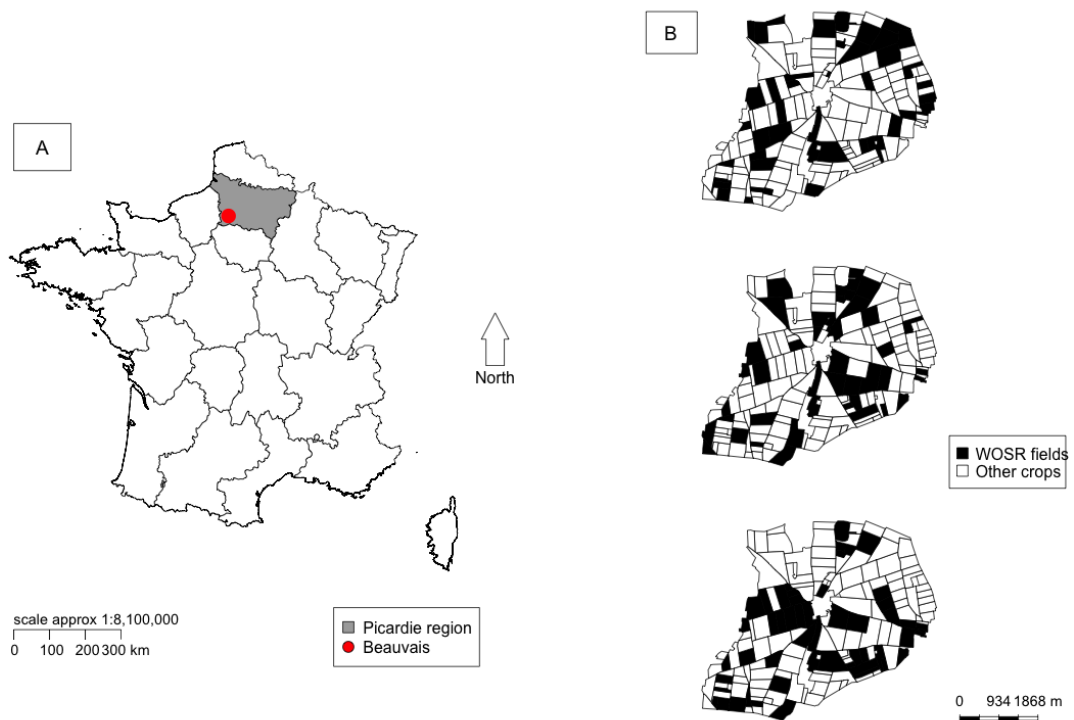
Figure 1. Organisation of the regional analysis of future scenarios: methods and expected results.

	<u>Methods</u>	<u>Outputs</u>
<i>Step A</i>	Participatory collective design	Cropping system scenarios
<i>Step B</i>	Simulations with SIPPOM-WOSR	Scenario evaluation
<i>Step C</i>	Comparison of scenario simulations to identify scenario minimizing each evaluation criterion	Identification of most efficient management scenarios
<i>Step D</i>	Meta-modelling of cropping practice impacts on the 3 disease indicators	Ranking of cropping practices according to their impacts on phoma control

Figure

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Figure 2. Location of (A) the studied region (in grey), location of the field map (red dot) and (B) Example of one year-random WOSR allocation (3 replicates of one scenario on the field map).

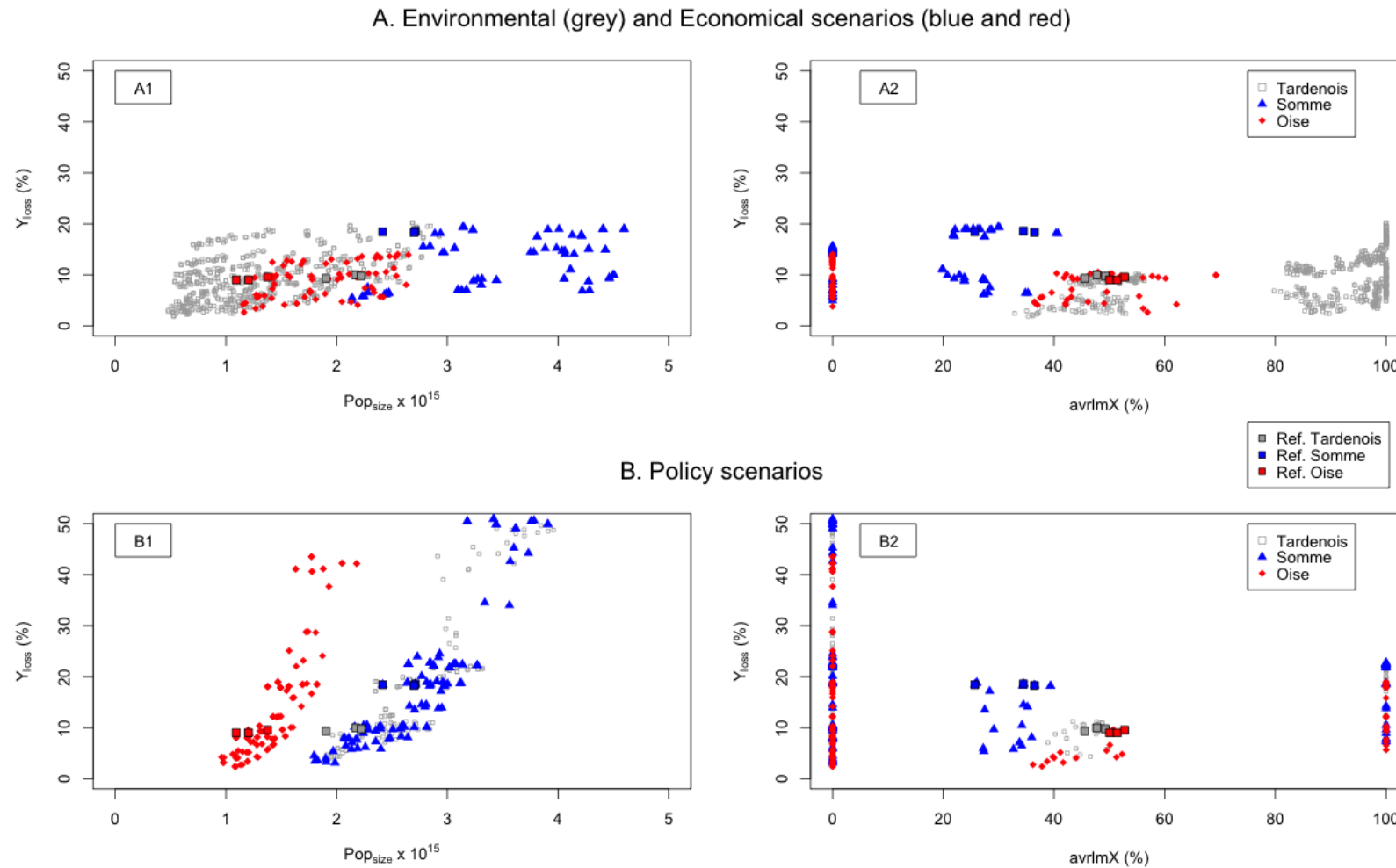


WOSR: Winter OilSeed Rape. Maps were created with the R software (R Development Core Team, 2013), using the R packages “GISTools” (Brunsdon and Chen, 2012), “maptools” (Bivand and Lewin-Koh, 2014), “maps” (Becker *et al.*, 2013) and “rgdal” (Bivand *et al.*, 2014).

Figure

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Figure 3. Reference situations and scenario simulation results for the three futures (Policy scenarios above (A); Environmental and economical scenarios below (B)) for the three evaluation criteria

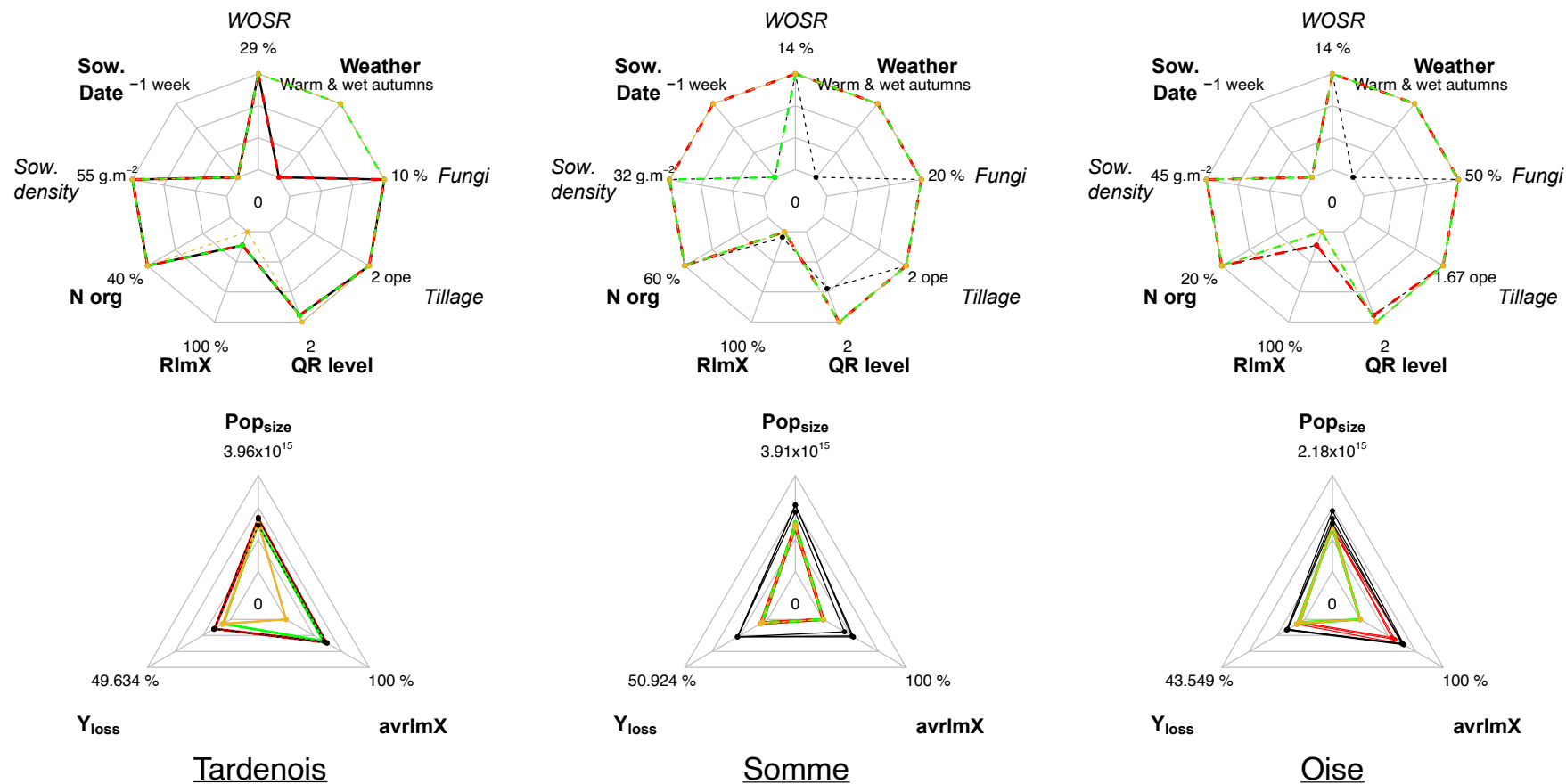


Yield losses on the y-axis; Size of the pathogen population or Frequency of the virulent pathotypes on RlmX-gene on the x-axis in left and right figures respectively.

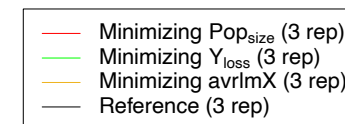
Figure

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Figure 4. Spider diagrams of scenarios minimizing each evaluation criteria for policy scenarios for the three sub-regions (cropping practices above; performances below).



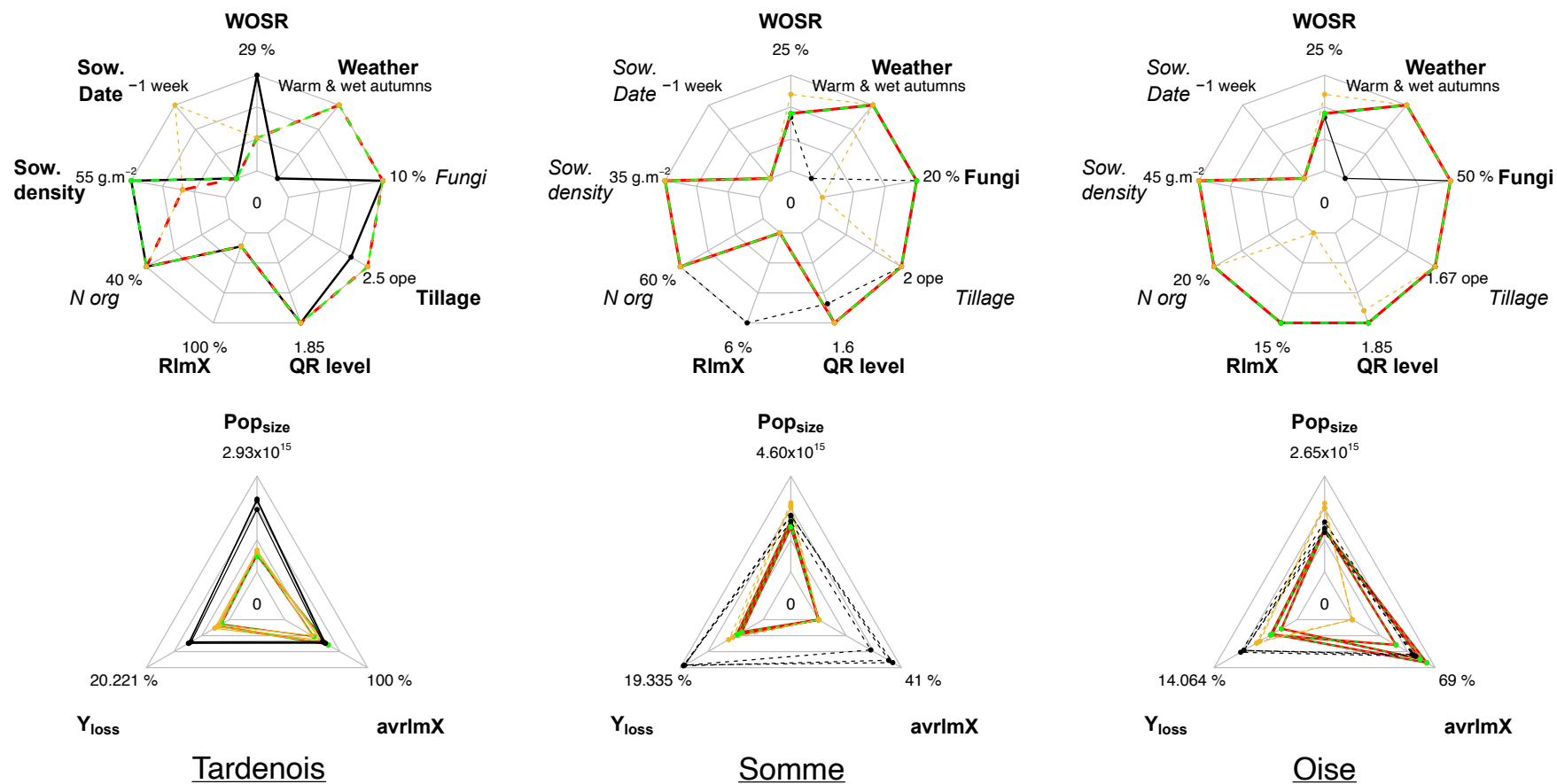
Minimum and maximum values of each diagram are deduced from the reference situation and all policy scenarios for each sub-region. Untested cropping practices are in italics. WOSR : winter oilseed rape areas ; Sow : sowing ; Fungi : fraction of WOSR areas with fungicide applications ; RlmX : fraction of WOSR areas with RlmX-cultivars ; Norg : fraction of WOSR areas with autumnal organic nitrogen application ; Tillage : number of tillage operations.



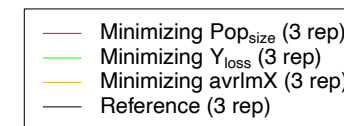
Figure

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Figure 5. Spider diagrams of scenarios minimizing each evaluation criteria for environmental scenarios (Tardenois) and economical scenarios (Somme and Oise) (cropping practices above; performances below).



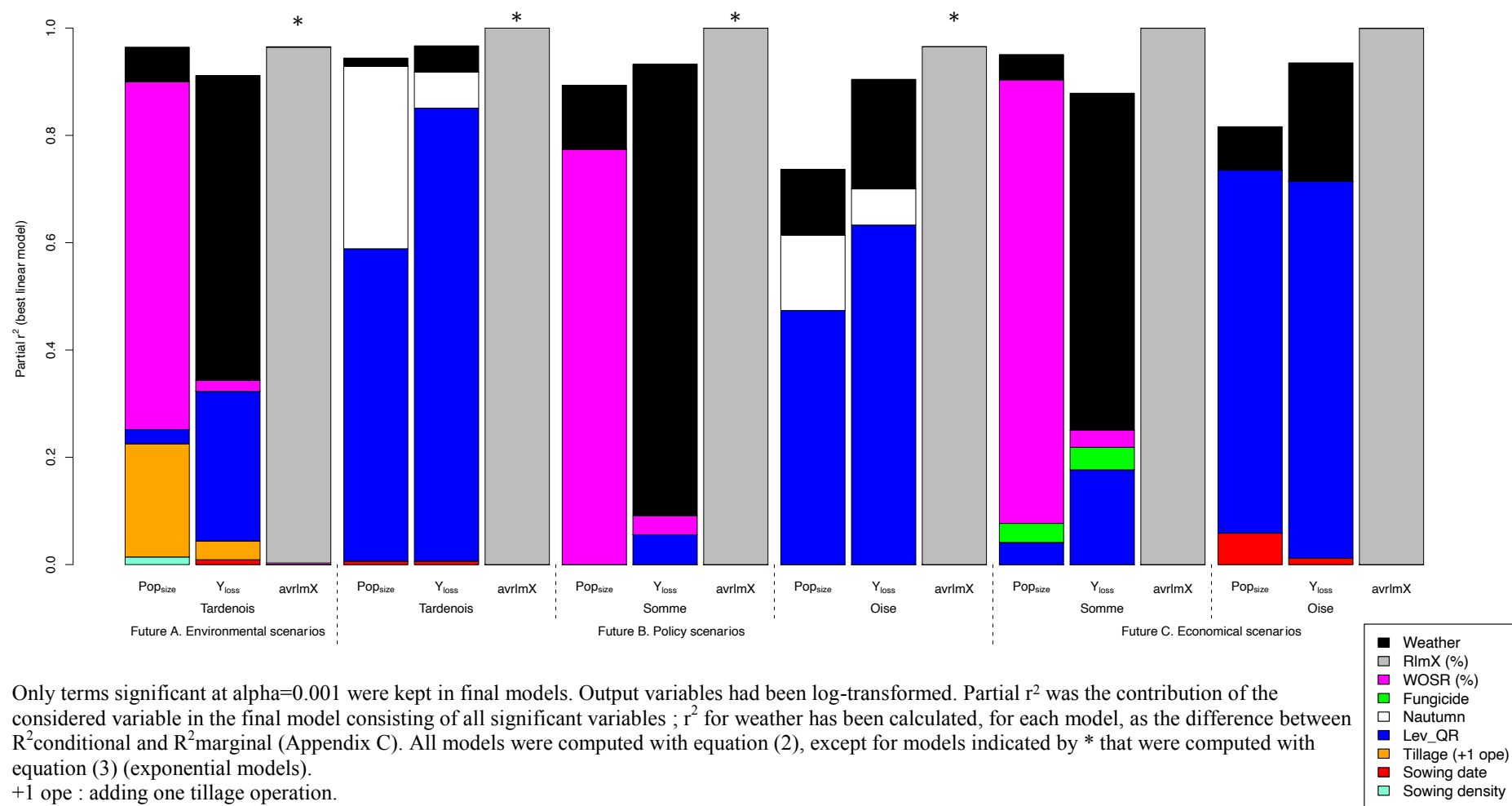
Minimum and maximum values of each diagram are deduced from the reference situation and all scenarios of the considered future for each sub-region. Untested cropping practices are in italics. WOSR : winter oilseed rape areas ; Sow : sowing ; Fungi : fraction of WOSR areas with fungicide applications ; RlmX : fraction of WOSR areas with RlmX-cultivars ; Norg : fraction of WOSR areas with autumnal organic nitrogen application ; Tillage : number of tillage operations.



Figure

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Figure 6. Final model contributions (partial r^2) of future scenarios' cropping practices to the three evaluation criteria (Pop_{size} , Y_{loss} and $avrlmX$) for each sub-region and future.



Only terms significant at $\alpha=0.001$ were kept in final models. Output variables had been log-transformed. Partial r^2 was the contribution of the considered variable in the final model consisting of all significant variables ; r^2 for weather has been calculated, for each model, as the difference between R^2 conditional and R^2 marginal (Appendix C). All models were computed with equation (2), except for models indicated by * that were computed with equation (3) (exponential models).
+1 ope : adding one tillage operation.

Table 1. Characteristics of reference situations and scenarios for the three futures in the different subregions (T: Tardenois, S: Somme and O: Oise).

Sub-region	Reference scenarios			Futures		
	Tardenois	Somme	Oise	T	T, S and O	S and O
Context change	-	-	-	Environmental scenario	Policy scenario	Economic scenario
WOSR frequency ¹	29%	14%	14%	10; 20%	ref	15; 20; 25%
Sowing dates	20/08-03/09	20/08-05/09	20/08-01/09	ref; One week in advance	ref; One week in advance	ref
Mean sowing densities (seeds.m ⁻²)	55	35	45	ref; 25	ref	ref
Nitrogen fertilisation ^{2,3}	40%	60%	20%	ref	ref ; 0	ref
Cultivars ³						
RlmX-cultivar	15%	6%	15%	ref; 100; 60; 40%	ref; 0; 0; 0; 100%	ref; 0%
High QR-cultivar	85%	26%	85%	ref; 0; 40; 60%	ref; 0; 0; 100; 0%	ref; 60%
Low QR-cultivar	0%	68%	0%	ref; 0; 0; 0%	ref; 0; 100; 0; 0%	ref; 40%
Sensible cultivar	0%	0%	0%	ref; 0; 0; 0%	ref; 100%; 0; 0; 0%	ref; 0%
Level of QR ⁴	1.85	1.26	1.85	ref; 1; 1.4; 1.6	ref; 0; 1; 2; 1	ref; 1.6
Tillage ²	100% 2 SB	100% RT + SB	67% 2 SB / 33% 1 SB	ref; 50% SB/50% 2 SB; 50% 2 SB/50% 3 SB	ref	ref
Fungicide ²	10%	20%	50%	ref	ref	ref; 10%
Weather		Current		Current (2003-2008); with mild and wet autums		
Number of scenarios ⁵	1	1	1	192	40	24

WOSR: Winter OilSeed Rape; QR: quantitative resistance; MB: moulboard ploughing; RT: rotary harrowing; SB: stubble breaking; ref: reference situation; ¹: % of cropped area (deduced from rotations); ²: % of WOSR area; ³: autumnal applications; ⁴: level of quantitative resistance (see Equation (1) for details); ⁵: for one repetition (i.e. one spatial allocation) and for each considered subregion.

Table 2. Effects of cropping practices (fixed effects) and weather (random effect on intercept) on the three evaluation criteria for the different futures and sub-regions.

Effect of...	On log(...) ^a	Environmental scenarios		Policy scenarios		Economic scenario	
		Tardenois	Tardenois	Somme	Oise	Somme	Oise
Wet and mild weather ^b	Size of pathogen population (Pop _{size})	-0.277	-0.044	-0.123	-0.104	-0.153	-0.100
An increase of 1% of WOSR		0.071				0.048	0.052
Sowing one week earlier		0.106	0.028	NS	0.090		
N-fertilizer on 1% of WOSR			-0.005	-0.002	NS		
Increasing QR level of 1		-0.233	-0.191	-0.191	-0.213	NS	-0.381
Adding 1 tillage		-0.499					
Using fungicide on 1% of WOSR						NS	-0.002
Wet and mild weather ^b	Yield loss (Y _{loss})	-0.804	-0.288	-0.608	-0.688	-0.766	-0.647
An increase of 1% of WOSR		0.015				0.019	0.018
Sowing one week earlier		0.102	NS	NS	0.160		
N-fertilizer on 1% of WOSR			-0.009	-0.006	NS		
Increasing QR level of 1		-0.906	-0.842	-0.838	-0.857	-0.580	-1.376
Adding 1 tillage		-0.244					
Using fungicide on 1% of WOSR							-0.003
Wet and mild weather ^b	Frequency of virulent pathotypes on RlmX-cultivars (avrlmX)	-0.018 ^c	NS ^c	NS ^c	NS ^c	NS	NS
An increase of 1% of WOSR ^d		<i>0.991^{c,d}</i>				-0.016	-0.012
An increase of 1% of RlmX-cultivars ^d		<i>0.935^{c,d}</i>	<i>0.818^{c,d}</i>	<i>0.643^{c,d}</i>	<i>0.815^{c,d}</i>	2.463	1.025

^aOutput variables have been log-transformed. ^brandom effect of weather on intercept only. All models were linear (Equation 2) except ^c (exponential models, Equation 3). ^dFor exponential models (in italics in the table), input variable effects are not linear, i.e. the indicated parameter has to be raised to the power of the considered variable (e.g. 0.991^{F_WOSR} , with F_WOSR the frequency of WOSR in the landscape) ; see Appendix D for complete equations. NS : variable not significant at alpha = 0.001. White box : untested factor. WOSR : areas cropped with winter oilseed rape ; QR : quantitative resistance.