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

Laure Hossard, Véronique Souchère, Elise Pelzer, Xavier Pinochet, Marie-Helene Jeuffroy

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Corresponding Author: Dr. Laure Hossard, Ph.D

Corresponding Author's Institution: INRA

First Author: Laure Hossard, Ph.D

Order of Authors: Laure Hossard, Ph.D; Véronique Souchère, Ph.D; Elise Pelzer, Ph.D; Xavier Pinochet, Ph.D; Marie-Hélène Jeuffroy, Ph.D

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

L. Hossard[1,2,3,4,5*], V. Souchere[3,4], E. Pelzer[1,2], X. Pinochet[6], M.H. Jeuffroy[1,2]

[1] INRA, UMR211 Agronomie, F-78850 Thiverval-Grignon, France

[2] AgroParisTech, UMR211 Agronomie, F-78850 Thiverval-Grignon, France

[3] INRA, UMR1048 SADAPT, F-78850 Thiverval-Grignon, France

[4] AgroParisTech, UMR1048 SADAPT, F-78850 Thiverval-Grignon, France

[5] INRA, UMR0951 Innovation, F-34000 Montpellier, France

[6] Cetiom, BP-04, F-78850 Thiverval-Grignon, France

* Corresponding author: Email laure.hossard@supagro.inra.fr; Phone +33 4 99 61 20 19; Fax: +33 4 67 54 58 43

Co-authors emails: souchere@grignon.inra.fr; pelzer@grignon.inra.fr; pinochet@cetiom.fr, jeuffroy@grignon.inra.fr

Abstract

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

1. Introduction

In agricultural landscapes, pest and disease control depends on cropping system characteristics. Disease severity is influenced by crop management practices modifying the host (i.e. the crop), the pathogen, or the environment (Krupinsky *et al*., 2002). Phoma stem canker (causal agent *Leptosphaeria maculans*) of Winter Oilseed Rape (WOSR; *Brassica napus*) is an internationally important disease responsible for large economic losses (Fitt *et al*., 2006). Its control currently relies mainly on the use of resistant cultivars, which have quantitative partial resistance, limiting crop damage, and/or qualitative specific resistance, limiting pest attacks. The specific resistance, based on gene-for-gene interaction (Flor, 1971), stops disease development when the crop carries a resistance gene and the pathogen carries the corresponding avirulence gene (Delourme *et al*., 2006). However, due to widespread use of the same resistance gene, qualitative resistance can be overcome in a few years (Rouxel *et al*., 2003), and requires management to increase the duration of effectiveness. Aubertot *et al*. (2006) showed that preservation of resistance and disease control can be improved by (i) managing pathogen population size (quantitative feature), and (ii) limiting the selection pressure on pathogen populations (qualitative feature). These epidemiological components may be influenced by landscape composition in terms of proportion of host crop (Fitt *et al*., 2006; Skelsey *et al*., 2010), of cultivars (e.g. on wheat leaf rust epidemics, Papaïx *et al*., 2011; on virus in Fabre *et al*., 2012), including resistance gene deployment (Pink and Puddephat, 1999), and cropping practices (e.g. on phoma stem canker of oilseed rape, Lo-Pelzer *et al*., 2010). Spatial organisation of WOSR fields during successive years also influences resistance sustainability (e.g. Lo-Pelzer *et al*., 2010). For phoma stem canker management, the design of control strategies requires scaling up from annual/field to multi-year/regional (Lo-Pelzer *et al*., 2010). Combining both resistance deployment and cropping practices in space and time may help disease control (Aubertot *et al*., 2006), since the epidemic cycles of this disease are characterized by year-to-year recurrence processes (Hall, 1992; Lo-Pelzer *et al*., 2009) and long-distance dispersal (5-8 km, Bokor *et al*., 1975).

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

Different methods can be used to design strategies at the landscape scale. In the case of agricultural landscapes, decisions about landscape changes and agricultural production are mainly taken by local farmers (Primdahl, 1999) and influenced by stakeholders acting at local and wider scales (e.g. crop collectors; markets). Based on their expertise on local agricultural conditions, stakeholders can envision possible technical changes (Carr and Halvorsen, 2001) in the face of modifications to the local and global context. These locally-decided proposals may be more suitable than generic ones (Brandenburg *et al.*, 1995), as they take into account more complete information (Reed, 2008) on technically-feasible options, constraints, flexibility (Joannon et al, 2006) and cost-effectiveness (Voinov and Bousquet, 2010). To provide useful elements for decision-making on a large spatial scale, a participatory approach can be beneficial, especially when the effective strategies involve the coordination of several stakeholders, including farmers (e.g. on risks from runoff erosion, Souchere *et al*., 2010). These scenarios may differ among various contexts (Hossard *et al*., 2013), such as economics (market prices of crops, etc.), which may promote or influence specific crop choices. Designing and assessing strategies of cropping systems with stakeholders may then help to identify reliable and suitable cropping system options that could be used to cope with future contextual changes. The objectives of this paper were to (1) identify scenarios allowing efficient disease control, and (2) assess and rank *ex ante* the impacts of different cropping system scenarios on the control of phoma stem canker on a regional scale.

2. Materials and methods

2.1. Method overview

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

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

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

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

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

Figure 1 approximately here

2.2. Study area

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

2.3. Scenario characteristics

In this study, a scenario is composed of detailed cropping practices linked to a contextual change. Scenarios generally include a reference situation and a description of driving forces for the future (Alcamo and Henrichs, 2008). Therefore local stakeholders first designed reference situations. Three reference situations of cropping systems were characterized, each corresponding to an agronomically uniform sub-region (Table 1). The stakeholders then imagined possible contextual changes (called futures), which would imply modifications in cropping practices (see Hossard *et al.* (2013) for details). Three types of scenario were designed: policy scenarios, environmental scenarios and economic scenarios. Policy scenarios were possible future contexts in which policies would be changed. Two types of policy were considered: the banning of autumn organic manuring of WOSR, and the exclusion of cultivar types from the market, obliging farmers to grow a single type of cultivar (defined by its resistance type - qualitative or quantitative - and its level of quantitative resistance).

The environmental scenarios supposed weed issues in WOSR that would require mitigation through changes in the crop sequence and increase the return time of WOSR. Environmental scenarios thus pointed to a decrease in the frequency of WOSR on a regional scale. Economic scenarios indicated a competitive advantage of WOSR over other crops due to its price, prompting an increase in the surface area of WOSR. Policy scenarios were applied to each of the three sub-regions. Environmental scenarios were applied to Tardenois, and economic scenarios were applied to Oise and Somme (Table 1).

Table 1 approximately here

Stakeholders described the possible modifications of cropping practices for each specific future (Table 1). They suggested two weather options: the current weather and one with greater extremes, such as warm wet autumns, *a priori* favourable to phoma development. Each combination of cropping characteristics and weather pattern defined a scenario to be simulated with the SIPPOM-WOSR model. The number of scenarios differed between futures due to the number of tested cropping practices and their options (Table 1). Three replicates of each scenario were performed, varying in the location of WOSR and associated cropping characteristics within the region, since no specific rule for crop or practice location was suggested by stakeholders (Figure 2). For each WOSR frequency, corresponding crop rotations were applied to fields, e.g. for a WOSR frequency of 50%, each field was cropped with WOSR one year out of two. WOSR frequencies were deduced from crop rotations designed by stakeholders. Autumn fungicide and organic nitrogen applications were defined as a fraction of WOSR areas with application. Fungicides were applied on October 20th (as now) at the current rate; nitrogen fertilizers were applied at sowing, using 80 kg of nitrogen per hectare, as indicated by stakeholders. For each future, stakeholders designed each cropping practice independently from each other.

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

Table 2 approximately here

Figure 2 approximately here

2.4. Model-based scenario simulation

2.4.1. Model description

SIPPOM-WOSR is a spatially-explicit model simulating the effects of spatially-distributed cropping systems on phoma stem canker. It integrates epidemiological, population and crop model approaches to simulate the evolution of *L. maculans* under considered cropping systems (see Lô-Pelzer *et al.* (2010) for details). The model inputs include the field plan of the considered region (field locations and related soil characteristics), local weather data (daily rainfall, temperature, wind direction and intensity, wetness duration, evapotranspiration and radiation), the genetic structure of the initial pathogen population (i.e. frequency of the considered avirulent genes) and its location (linked with WOSR-field locations in the initialization simulation year), the spatially distributed cropping systems (annual location of WOSR fields and applied cultivation techniques, i.e. sowing time and density, cultivar, autumn nitrogen fertilization, fungicide application, harvest time, tillage operation after WOSR harvest and sowing date of the next crop). These input variables influence the annual life cycle of the pathogen, *Leptospheria maculans,* and WOSR crop growth through five sub-models: primary inoculum production, pathogen dispersal, pathogen genetic evolution, crop growth, and crop infection and yield loss. Model outputs are annual yield loss (due to phoma stem canker), pathogen population structure, and size defined at field and field map scales.

2.4.2. Scenario simulations

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

2.5. Analyses of scenario performance

2.5.1. Preliminary analyses

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

To represent qualitative and quantitative resistance on evaluation criteria, two indicators were averaged at the regional scale: the frequency of RlmX-cultivars (in % of cropped WOSR) and a synthetic indicator describing quantitative resistance (Quantitative Resistance level, or QR level). For each scenario, QR level was calculated as:

$$QR\_lev_i = \sum_{j=1}^{n} a_j \,.\, Cv_{ij} \text{ (Equation 1)}$$

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

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

2.5.2. Identification of efficient scenarios

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

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

We developed linear mixed models to test the effects of cropping practices on the three evaluation criteria for each future and sub-region. For the complete models, we included and tested eight possible explanatory variables: frequency of WOSR in the landscape (as % of cropped area), sowing date (current vs. early), sowing density (in seeds.m^{-2}), percentage of WOSR-areas with organic nitrogen fertilization (as % of cropped WOSR where a rate of 80 kgN.ha^{-1} is applied), frequency of RlmX-cultivars (as % of cropped WOSR), level of quantitative resistance (QR, see Equation 1 above), tillage practices (number of operations), and use of fungicide (as % of cropped WOSR, current product and rate of application) (Table 1). The weather effect (current vs. weather with wet and warm autumns; Table 1) was described using an additive random effect only, since farmers cannot control this variable. Each cropping practice was analysed independently and no interactions were included because stakeholders designed cropping practices that were independent of each other (and of weather). This suggests that farmers would manage the tested cropping practices independently.

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

$Pop\_size_{ijk} = a_{0k} + a_1.F\_WOSR_{ij} + a_2.Sow\_Date_{ij} + a_3.Sow\_Density_{ij} + a_4.N\_org_{ij} + a_5.QR\_lev_{ij} + a_6.Tillage_{ij} + a_7.Fungi_{ij} + \varepsilon_{ij}$, with $\varepsilon_{ij} \sim N(0, \tau^2)$ and $a_{0k} \sim N(a_0, \sigma_0^2)$ (Equation 2)

$avrlmX_{ijk} = a_{0k}.(1 - \exp(a_1.F\_WOSR_{ij} + a_2.Sow\_Date_{ij} + a_3.Sow\_Density_{ij} + a_4.N\_org_{ij} + a_5.F\_RlmX_{ij} + a_6.Tillage_{ij} + a_7.Fungi_{ij} + a_8)) + \varepsilon_{ij}$, with $\varepsilon_{ij} \sim N(0, \tau^2)$ and $a_{0k} \sim N(a_0, \sigma_0^2)$

(Equation 3)

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

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

Models (2-3) were compared for each criterion separately, based on the Akaike information criterion (AIC). Only significant explanatory variables (alpha = 0.001) were kept in the models. For each evaluation criterion, these models were also compared to a constant model without explanatory variables and random effects. The distributions of the residuals of the models showing the lowest AIC were symmetrical and did not show any trend. The models showing the lowest AIC were selected to analyse the effects of the cropping system scenario on the evaluation criteria. Only the models with the lowest AIC are presented here.

Determination coefficients (R^2) were calculated to characterize the best models (i.e. with the lowest AIC). We used the method proposed by Nakagawa and Schielzeth (2013) for mixed-models. For each model, two determination coefficients were calculated: marginal R^2 is the variance explained by only the fixed factors; conditional R^2 is the variance explained by the fixed and the random effects.

2.5.4. Statistical analysis

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

3. Results

3.1. Reference and future simulations’ results

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

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

Pop_{size} (2.6 x10^{15} spores on average) as compared to Tardenois (2 x 10^{15} spores) and Oise (1.2 x10^{15} spores) (Figure 3A1). Simulated yield loss in the reference situation did not differ between replicates (i.e. spatial allocations, see Figure 1) for the three sub-regions. Oise and Tardenois had similar simulated avrlmX; it was smaller for Somme. Simulated references were more diverse for the size of the pathogen population in the three sub-regions, with standard deviations of 1.4 x 10^{14} spores in Oise and 1.7 x 10^{14} in Tardenois and Somme sub-regions (Figure 3A1).

In the policy scenarios, the range of simulated yield loss was similar in all sub-regions (2-44%, 3-51% and 4-50% of virulent pathotypes for Oise, Somme and Tardenois respectively); simulated Y_{loss} were mainly higher than the reference (Figure 3B1). The simulated sizes of pathogen populations were lower for the sub-region Oise (1-2.2 x10^{15} spores) than for the two other sub-regions (1.8-3.9 and 1.9-4 x10^{15} spores for Somme and Tardenois respectively). For Somme and Tardenois, policy scenarios mainly led to higher Popsize compared to reference situations (Figure 3B1). The simulated avrlmX ranged between almost 0 % (10^{-5}%) and 100% of virulent pathotypes for the three subregions, corresponding to scenarios with 0 and 100% of cropped RlmX-cultivars respectively (data not shown). In scenarios using reference cultivars (Table 1), simulated avrlmX were closer to the reference situations. For Somme sub-region (6% of RlmX-cultivars), avrlmX ranged between 26 and 39%. For Oise and Tardenois (15% of RlmX cultivars), simulated avrlmX were higher (36-53% and 39-51% respectively) (Figure 3B2).

In the sub-region Tardenois, simulation of environmental scenarios mainly outperformed reference situations for simulated Pop_{size} (0.48-2.93 x10^{15} spores, with 88% of scenarios lower than reference Pop_{size}) (Figure 3A1). Yield loss varied between 2 and 20%. All simulated pathotypes were virulent on RlmX-cultivars (avrlmX) for scenarios where only RlmX-cultivars were grown. Simulated avrlmX decreased for scenarios with fewer RlmX-cultivars:

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

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

Figure 3 approximately here

3.2. Scenarios minimizing phoma evaluation criteria

In the different futures, the three evaluation criteria of phoma control (Y_{loss}, Pop_{size} and avrlmX) were rarely minimized by the same combinations of cropping practices. Moreover, scenarios minimizing one evaluation criterion may not be efficient for another (Figures 4 and 5). These results are consistent with those of correlation tests. Pearson correlations indicated a relative independence between Pop_{size} and avrlmX, with either non-significant correlations (alpha = 0.05) or very low coefficients of determination (R^2<0.08) (Appendix A). Correlations were also low between Y_{loss} and avrlmX (R^2<0.22). Only correlations between Pop_{size} and Y_{loss} were consistently significant (alpha=0.001), with high determination coefficients for policy scenarios (0.69-0.77) and lower ones for environmental and economic scenarios (R^2 between 0.19-0.22) (Appendix A).

Two diagrams were drawn for each future and sub-region to compare and illustrate minimization scenarios. The first illustrates cropping practices for the three scenarios; the second shows the three evaluation criteria for the three scenarios. Maximum values are at the edges of the diagrams; minimum values are at the center of the spider diagram. We included zero values for the evaluation criteria and for quantitatively described cropping practices. Current weather is at the centre of the diagram and the option with warm wet autumns at the edge. Current sowing dates are at the centre of the diagram. Minimum and maximum values for diagrams were determined by considering the reference situation and all scenarios of the future concerned for each sub-region.

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

Figure 4 approximately here

In the environmental scenarios, single-criterion minimization scenarios always performed well on the other two criteria. They all included small areas with WOSR (10%), an increased tillage intensity and a high level of quantitative resistance, involving a low use of RlmX-cultivars. Simulated avrlmX was lowered with early sowing; Y_{loss} and avrlmX were decreased by decreasing sowing density (Tardenois in Figure 5).

In the economic scenarios, those minimizing Y_{loss} and Pop_{size} performed similarly for the three criteria in the Somme and Oise sub-regions, but corresponded to highest avrlmX in Oise (Figure 5). In Oise, scenarios minimizing avrlmX corresponded to highest Pop_{size} and Y_{loss}. Similarly, some cropping practices maximizing phoma control differed between Somme and Oise. Pop_{size} and Y_{loss} were minimized by a low cropping of WOSR (15%); avrlmX was minimized by a medium cropping of WOSR (20%) in both sub-regions (Somme and Oise in Figure 5). For the Oise sub-region, avrlmX was minimized when no RlmX-cultivar was grown; but Yloss and Popsize were minimized at 15% or RlmX-cultivars. This was not the case for the Somme sub-region, where all criteria were minimized without RlmX-cultivars. All minimization scenarios for economic scenarios included high use of fungicide (Somme and Oise in Figure 5).

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

Figure 5 approximately here

3.3. Scenario replicates

For each scenario of each future, the three scenario replicates (i.e. spatial allocation, Figure 2) minimizing one evaluation criterion were very close with regards to the other criteria; i.e. the three replicates of the scenario minimizing Y_{loss} ranked similarly for Pop_{size} and avrlmX (Figures 4 and 5), with one exception. In the Oise sub-region and for the economic future, the replicates minimizing the size of the pathogen population differed for both Yloss (2-5%) and avrlmX (37-62%) (Oise, Figure 5). However, there were no significant differences between replicates (alpha=0.001) for each evaluation criterion, sub-region or future. All regression models analysing the effects of cropping practices on evaluation criteria provided determination coefficients larger than 0.83, except for the size of the pathogen population for economic scenarios in the sub-region Oise (R^2=0.62) (Appendix B).

3.4. Effect of cropping system characteristics on phoma control

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

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

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

WOSR area impacted simulated Pop_{size} primarily in the environmental and economic futures (Figure 6); an increase of 1% in WOSR area increased the logarithm of the size of the pathogen population of about 5-7 x 10^{13} spores (Table 2). The effect of WOSR fraction on yield loss was lower. Y_{loss} and Pop_{size}, especially the former, depended heavily on the level of quantitative resistance, especially for policy scenarios (Table 2). In policy scenarios, the increase in area with nitrogen fertilization decreased Pop_{size} and Y_{loss} in Tardenois and Somme; in Oise, sowing one week before current practice increased these two evaluation criteria (Table 2). In environmental scenarios, log(Pop_{size}) decreased by 5 x 10^{14} spores and log(Y_{loss}) decreased by 0.25% (Table 2).

Figure 6 approximately here

Table 2 approximately here

4. Discussion

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

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

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

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

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

sometimes significant) on the assessment criteria: for instance increased autumn nitrogen fertilization significantly decreased yield loss for the three sub-regions (Table 2). These results differ from those of other studies (e.g. Aubertot *et al*., 2004) but are consistent with the stakeholders' views. Moreover, the rates of nitrogen used in the cited study are very high (250 $kgN.ha^{-1}$; Aubertot *et al.*, 2004) as compared to current rates (here 80 $kgN.ha^{-1}$).
The impact of warm wet weather was usually significantly negative, but its importance depended on cropping practices tested (Table 2). The effect of warm wet autumns reduced yields more than it reduced spore numbers, whose main drivers were either the positive effect of the WOSR area or cultivar type. Using a weather dataset likely to present favourable conditions for phoma stem canker development decreased yield loss and the size of the pathogen population in all futures. Salam *et al*. (2011) find similar effects of climate on blackspot in field peas. This could be linked with the model behaviour: with the temperature being higher, rape plants would grow faster, reaching the 6-leaf stage earlier in the season (when plants become highly resistant to primary inoculum, whatever the cultivar; Brunin and Lacoste, 1970). Thus the time for pathogen dispersal to be successful in infecting plants would be reduced, and in the event of global warming, this might decrease the risk from phoma. Weather has also been found to modify disease incidence in other pathosystems. For grapevine moth and powdery mildew, Caffarra *et al*. (2012) find that an increase of temperature has a detrimental effect on crop yield. However, this is due to the temperature effects on the asynchrony of pathogen and crop resistance (Caffara *et al*., 2012). Similarly, in the case of potato late blight, Skelsey *et al.* (2010) show the impact of weather on the coincidence in time and space of the pathogen and the crop susceptibility stage. Skelsey *et al*. (2010) find different effects of management strategies according to meteorological conditions, e.g. direction of spore dispersal by wind. In our study, stakeholders tested weather condition

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

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

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

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

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6. References

Alcamo, J., Henrichs, T., 2008. Toward guidelines for environmental scenario analysis. In: Alcamo, J. (Ed.), Environmental Futures. The Practice of Environmental Scenario Analysis. Elsevier, Amsterdam, The Netherlands, pp. 13-35.

Anderson, J., Clement, J., Crowder, L.V., 1998. Accomodating conflicting interests in forestry - concepts emerging from pluralism. Unasylva 49, 3-10.

Andrivon, D., Pilet, F., Montarry, J., Hafidi, M., Corbiere, R., Achbani, E.H., Pelle, R., Elliseche, D., 2007. Adaptation of Phytophtora infestans to partial resistance in potato : evidence from French and Moroccan populations. Ecology and Epidemiology, 97(3), 338-343.

Aubertot, J.N., Pinochet, X., Dore, T., 2004. The effects of sowing date and nitrogen availability during vegetative stages on Leptosphaeria maculans development on winter oilseed rape. Crop Protection 23, 635-645.

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

Becker, R.A., Wilks, A.R. (original S code), Brownrigg, R. (R version), Minka, T.P. (enhancements), 2013. Maps: Draw Geographical Maps. R package version 2.3-6. http://cran.r-project.org/web/packages/maps/index.html (accessed, June 2014).

Bergez, J.E., Colbach, N., Crespo, O., Garcia, F., Jeuffroy, M.H., Justes, E., Loyce, C., Munier-Jolain, N., Sadok, W., 2010. Designing crop management systems by simulation. European Journal of Agronomy 32, 3-9.

Bivand, R., Keitt,T., Rowlingson, B., 2014. rgdal: Bindings for the Geospatial Data Abstraction Library. R package version 0.8-16. http://CRAN.R-project.org/package=rgdal. (accessed, June 2014).

Bivand, R., Lewin-Koh, N., 2014. maptools: Tools for reading and handling spatial objects. R package version 0.8-29. http://CRAN.R-project.org/package=maptools. (accessed, June 2014).

Bokor, A., Barbetti, M.J., Brown, A.G.P., Mac Nish, G.C., P.McR, W., 1975. Blackleg of Rapeseed. Journal of Agriculture, Western Australia 16, 7-10.

Brandenburg, A.M., Carrol, M.S., Blatner, K.A., 1995. Towards successful forest planning through local based qualitative sociology. Western Journal of Applied Forestry. 10, 95-99.

Brun, H., Chevre, A.M., Fitt, B.D.L., Powers, S., Besnard, A.L., Ermel, M., Huteau, V., Marquer, B., Eber, F., Renard, M., Andrivon, D., 2010. Quantitative resistance increases the durability of qualitative resistance to Leptosphaeria maculans in Brassica napus. New Phytologist 185, 285-299.

Brunin, B., Lacoste, L., 1970. Recherches sur la maladie du colza due a Leptosphaeria maculans (Desm.) Ces. & de Not. II. pouvoir pathogene des ascospores. Annales de Phytopatholy. 6, 477–488.

Brunsdon, C., Chen, H. 2012. GISTools: Some further GIS capabilities for R. R package version 0.7-1 (2012). http://cran.r-project.org/web/packages/GISTools/index.html (accessed, June 2014).

Caffarra, A., Rinaldi, M., Eccel, E., Rossi, V., Pertot, I., 2012. Modelling the impact of climate change on the interaction between grapevine and its pests and pathogens: European grapevine moth and powdery mildew. Agriculture Ecosystems & Environment 148, 89-101.

Carr, D.S., Halvorsen, K., 2001. An evaluation of three democratic, community-based approaches to citizen participation: surveys, conservations with community groups, and community dinners. Society and Natural Resources 14, 107–126.

Colbach, N., 2010. Modelling cropping system effects on crop pest dynamics: How to compromise between process analysis and decision aid. Plant Science 179, 1-13.

Colbach, N., Kurstjens, D.A.G., Munier-Jolain, N.M., Dalbies, A., Dore, T., 2010. Assessing non-chemical weeding strategies through mechanistic modelling of blackgrass (Alopecurus myosuroides Huds.) dynamics. European Journal of Agronomy 32, 205-218.

Colbach, N., Molinari, N., Meynard, J.M., Messean, A., 2005. Spatial aspects of gene flow between rapeseed varieties and volunteers. Agronomy for Sustainable Development 25, 355-368.

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

Dougill, A.J., Fraser, E.D.G., Holden, J., Hubacek, K., Prell, C., Reed, M.S., Stagl, S., Stringer, L.C., 2006. Learning from doing participatory rural research: Lessons from the Peak District National Park. Journal of Agricultural Economics 57, 259-275.

Fabre, F., Rousseau, E., Mailleret, L., Moury, B., 2012. Durable strategies to deploy plant resistance in agricultural landscapes. New Phytologist 193, 1064-1075.

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

Flor, H.H., 1971. Current status of the gene-for-gene concept. Annual Review of Phytopathology 9, 275-296.

Hall, R., 1992. Epidemiology of blackleg of oilseed rape. Canadian Journal of Plant Pathology-Revue Canadienne De Phytopathologie 14, 46-55.

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

Huang, Y.J., Pirie, E.J., Evans, N., Delourme, R., King, G.J., Fitt, B.D.L., 2009. Quantitative resistance to symptomless growth of Leptosphaeria maculans (phoma stem canker) in Brassica napus (oilseed rape). Plant Pathology 58, 314-323.

Huang, Y.J., Qi, A., King, G.J., Fitt, B.D.L., 2014. Assessing quantitative resistance against Leptospheria maculans (Phoma stem canker) in Brassica napus (Oiseed rape) in young plants. Plos One 9(1), e84924.

Krupinsky, J.M., Bailey, K.L., McMullen, M.P., Gossen, B.D., Turkington, T.K., 2002. Managing plant disease risk in diversified cropping systems (vol 94, pg 198, 2002). Agronomy Journal 94, 955-955.

Joannon, A., Souchere, V., Martin, P., Papy, F., 2006. Reducing runoff by managing crop location at the catchment level, considering agronomic constraints at the farm level. Land Degradation & Development 17, 467-478.

Lautenbach, S., Berlekamp, J., Graf, N., Seppelt, R., Matthies, M., 2009. Scenario analysis and management options for sustainable river basin management: Application of the Elbe DSS. Environmental Modelling & Software 24, 26-43.

Legg, D.E., 2004. The relevance of modelling in successful implementation of IPM, in: Koul, O., Dhaliwal, G.S. (eds), Integrated pest management: potential, constraints and challenges. Cabi publ., Oklahoma state University, United States, pp. 39-54.

Lo-Pelzer, E., Aubertot, J.N., David, O., Jeuffroy, M.H., Bousset, L., 2009. Relationship between severity of blackleg (Leptosphaeria maculans/L-biglobosa species complex) and subsequent primary inoculum production on oilseed rape stubble. Plant Pathology 58, 61-70.

Lo-Pelzer, E., Bousset, L., Jeuffroy, M.H., Salam, M.U., Pinochet, X., Boillot, M., Aubertot, J.N., 2010. SIPPOM-WOSR: A Simulator for Integrated Pathogen POpulation Management of phoma stem canker on Winter OilSeed Rape I. Description of the model. Field Crops Research 118, 73-81.

Nakagawa, S., Schielzeth, H., 2013. A general and simple method for obtaining R2 from generalized linear mixed-effects models. Methods in Ecology and Evolution 4(2), 133–142.

Nakasawa, M., 2010. fmsb: Functions for medical statistics book with some demographic data. R package version 0.2.

Papaïx, J., Goyeau, H., Du Cheyron, P., Monod, H., Lannou, G., 2011. Influence of cultivated landscape composition on variety resistance : an assessment based on wheat leaf rust epidemics. New Phytologist 191, 1095-1107.

Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D. and the R Development Core Team, 2013. nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1-113.

Pink, D., Puddephat, I., 1999. Deployment of disease resistance genes by plant transformation - a 'mix and match' approach. Trends in Plant Science 4, 71-75.

Plantegenest, M., Le May, C., Fabre, F., 2007. Landscape epidemiology of plant diseases. Journal of the Royal Society Interface 4, 963-972.

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

R Development Core Team, 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0 (2011). http://www.R-project.org (accessed: November 2013).

Reed, M.S., 2008. Stakeholder participation for environmental management: a literature review. Biological Conservation 141 (10), 2417-2431.

Rounsevell, M.D.A., Ewert, F., Reginster, I., Leemans, R., Carter, T.R., 2005. Future scenarios of European agricultural land use. II. Projecting changes in cropland and grassland. Agriculture, Ecosystems & Environment 107, 117-135.

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

Savary, S., Teng, P.S., Willocquet, L., Nutter, F.W., 2006. Quantification and modeling of crop losses: A review of purposes. Annual Review of Phytopathology 44, 89-112.

Salam, M.U., MacLeod, W.J., Salam, K.P., Maling, T., Barbetti, M.J., 2011. Impact of climate change in relation to ascochyta blight on field pea in Western Australia. Australasian Plant Pathology, 40(4), 397-406.

Schneider, O., Roger-Estrade, J., Aubertot, J.N., Dore, T., 2006. Effect of seeders and tillage equipment on vertical distribution of oilseed rape stubble. Soil & Tillage Research 85, 115-122.

Skelsey, P., Rossing, W.A.H., Kessel, G.J.T., van der Werf, W., 2010. Invasion of Phytophthora infestans at the Landscape Level: How Do Spatial Scale and Weather Modulate the Consequences of Spatial Heterogeneity in Host Resistance? Phytopathology 100, 1146-1161.

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

Tricault, Y., Darmency, H., Colbach, N., 2009. Identifying key components of weed beet management using sensitivity analyses of the GeneSys-Beet model in GM sugar beet. Weed Research 49, 581-591.

van den Bosch, F., Gilligan, C.A., 2003. Measures of durability of resistance. Phytopathology 93, 16-625.

Viaud, V., Monod, H., Lavigne, C., Angevin, F., Adamczyk, K., 2008. Spatial sensitivity of maize gene-flow to landscape pattern: a simulation approach. Landscape Ecology 23, 1067-1079.

Voinov, A., Bousquet, F., 2010. Modelling with stakeholders. Environmental Modelling & Software 25, 1268-1281.

Wechsung, F., Krysanova, V., Flechsig, M., Schaphoff, S., 2000. May land use change reduce the water deficiency problem caused by reduced brown coal mining in the state of Brandenburg ? Landscape and Urban Planning 51, 177-189.

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

	Methods	**Outputs**
Step A	Participatory collective design	Cropping system scenarios
Step B	Simulations with SIPPOM-WOSR	Scenario evaluation
Step C	Comparison of scenario simulations to identify scenario minimizing each evaluation criterion	Identification of most efficient management scenarios
Step D	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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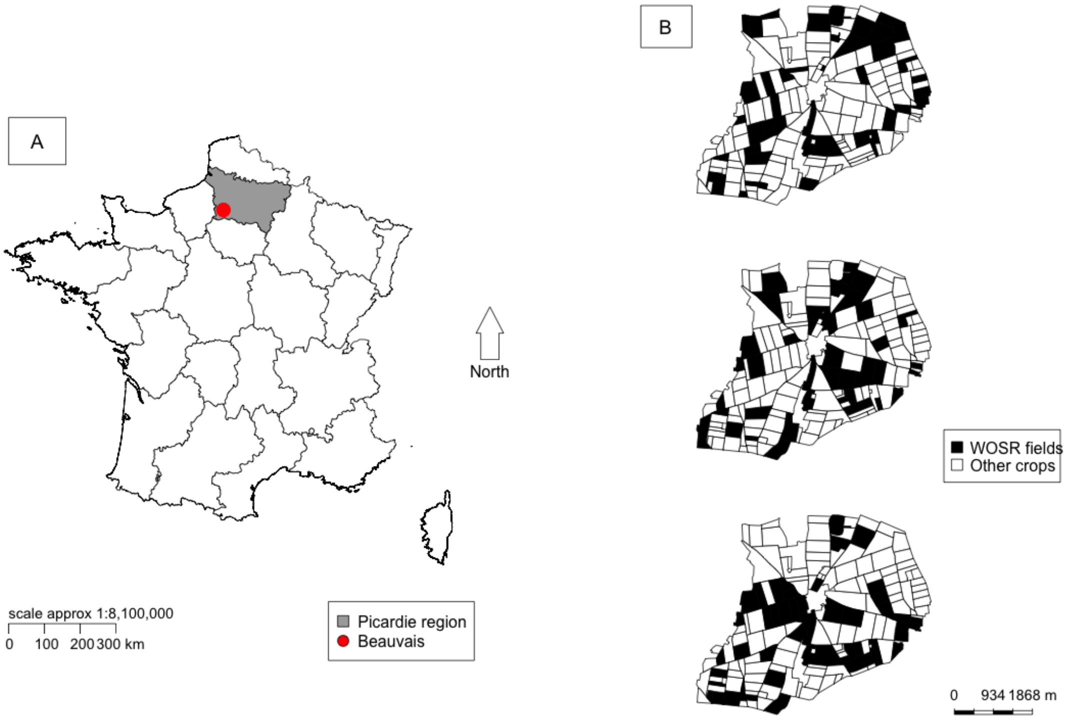
Figure 2. Location of (A) the studied region (in grey), location of the field map (red dot) and (B) Example of one year-random WOSR allocation (3 replicates of one scenario on the field map).



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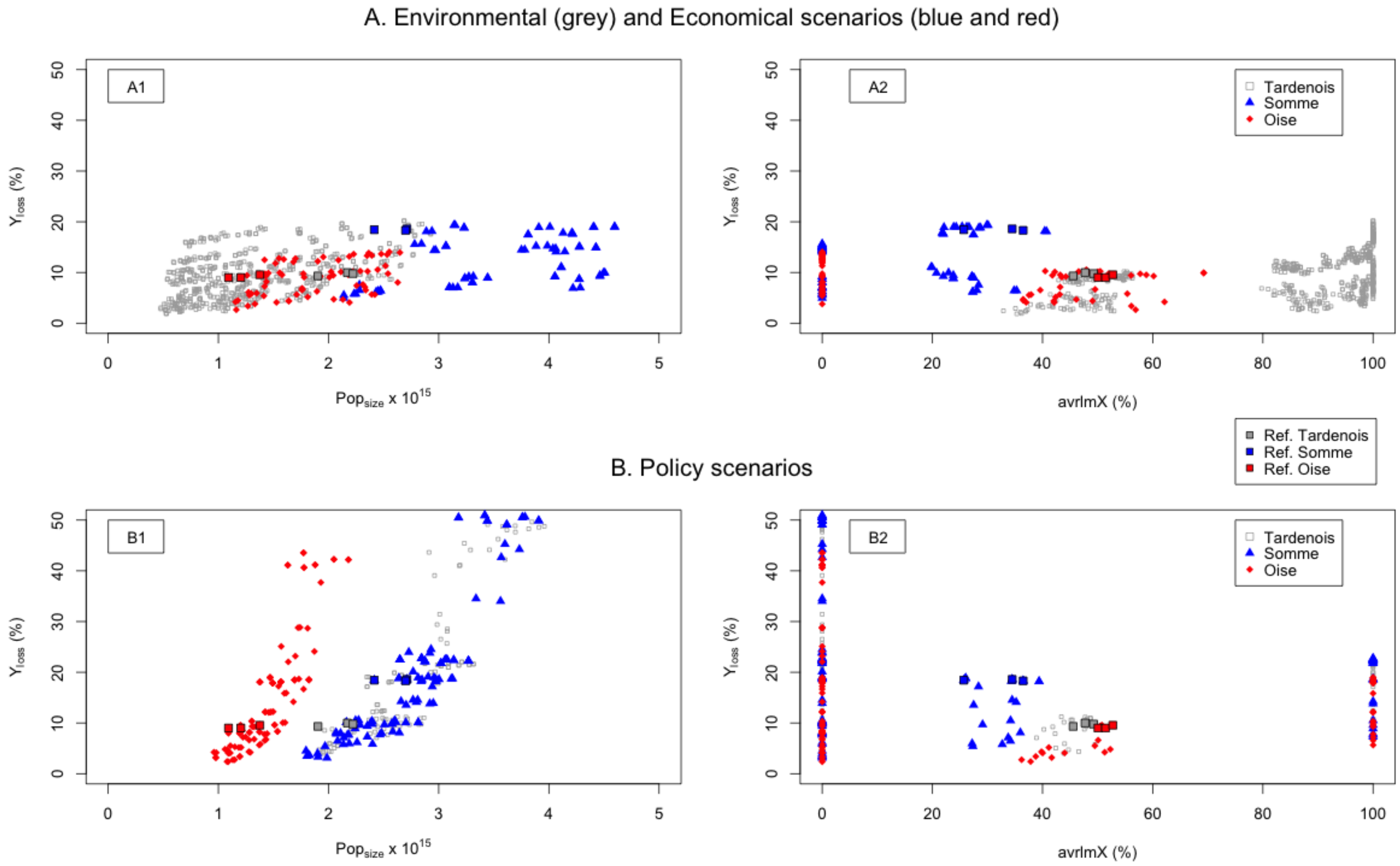
Figure 3. Reference situations and scenario simulation results for the three futures (Policy scenarios above (A); Environmental and economical scenarios below (B)) for the three evaluation criteria



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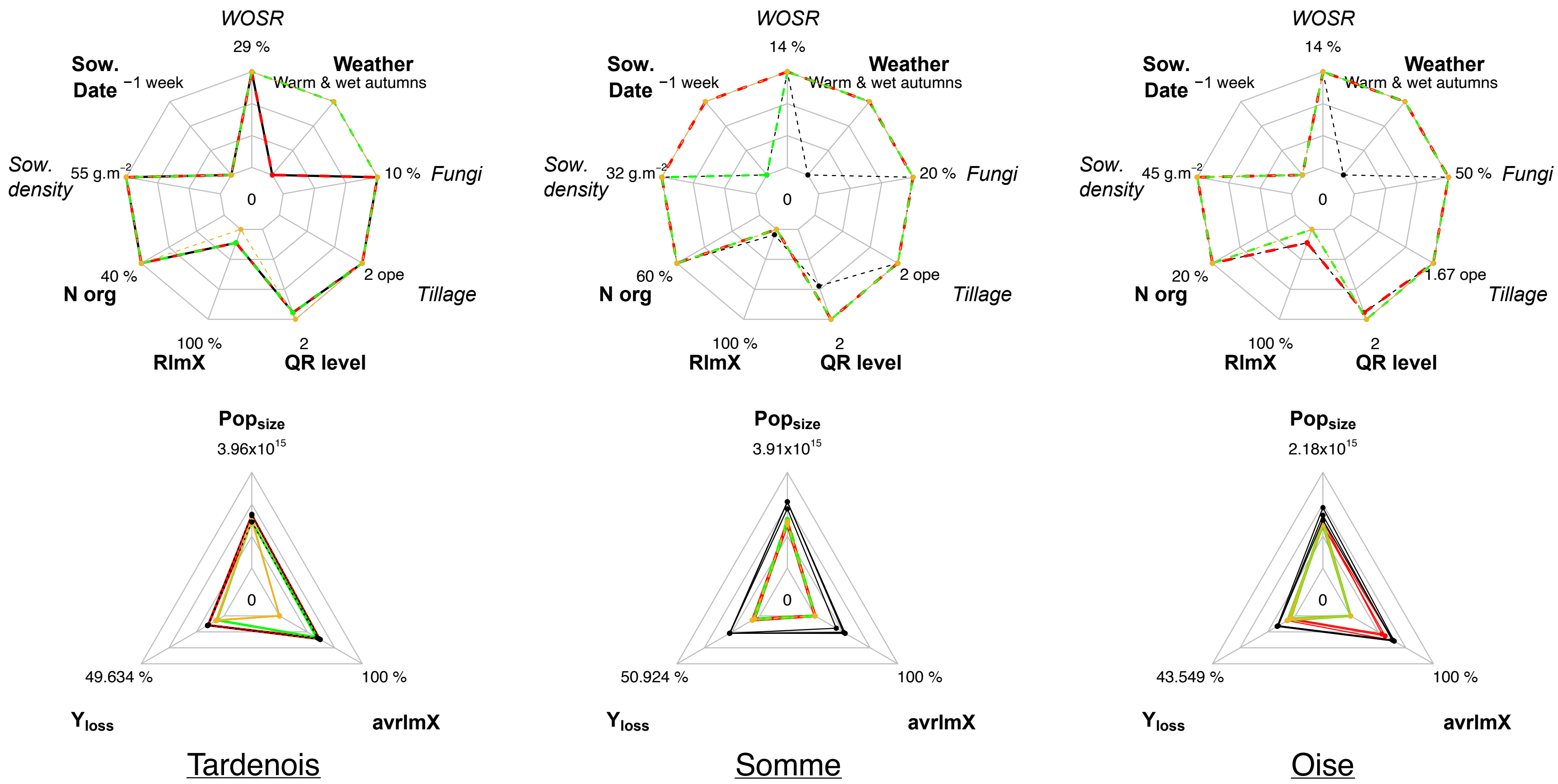
Figure 4. Spider diagrams of scenarios minimizing each evaluation criteria for policy scenarios for the three sub-regions (cropping practices above; performances below).



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.

Minimizing Pop_{size} (3 rep)
Minimizing Y_{loss} (3 rep)
Minimizing avrlmX (3 rep)
Reference (3 rep)

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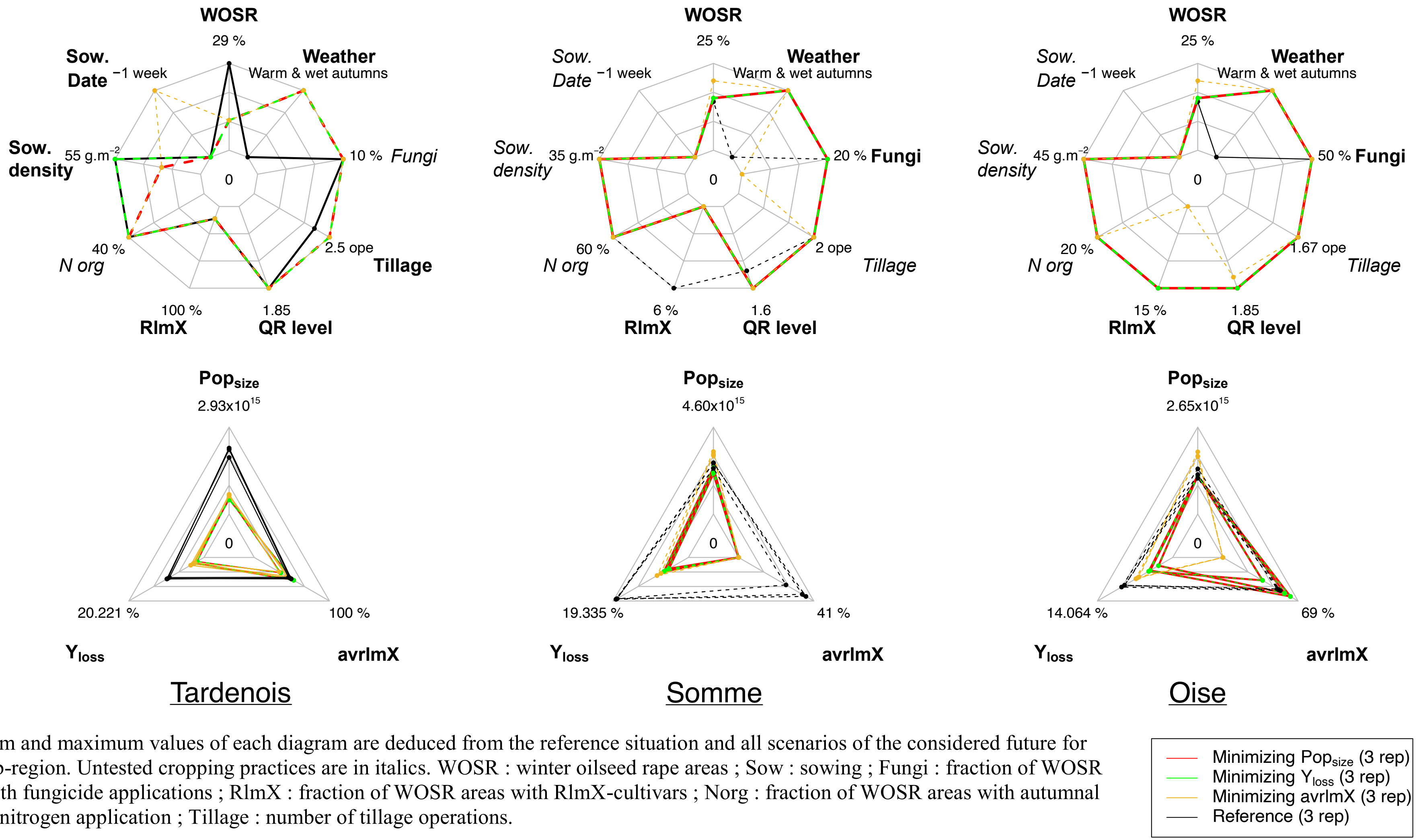
Figure 5. Spider diagrams of scenarios minimizing each evaluation criteria for environmental scenarios (Tardenois) and economical scenarios (Somme and Oise) (cropping practices above; performances below).



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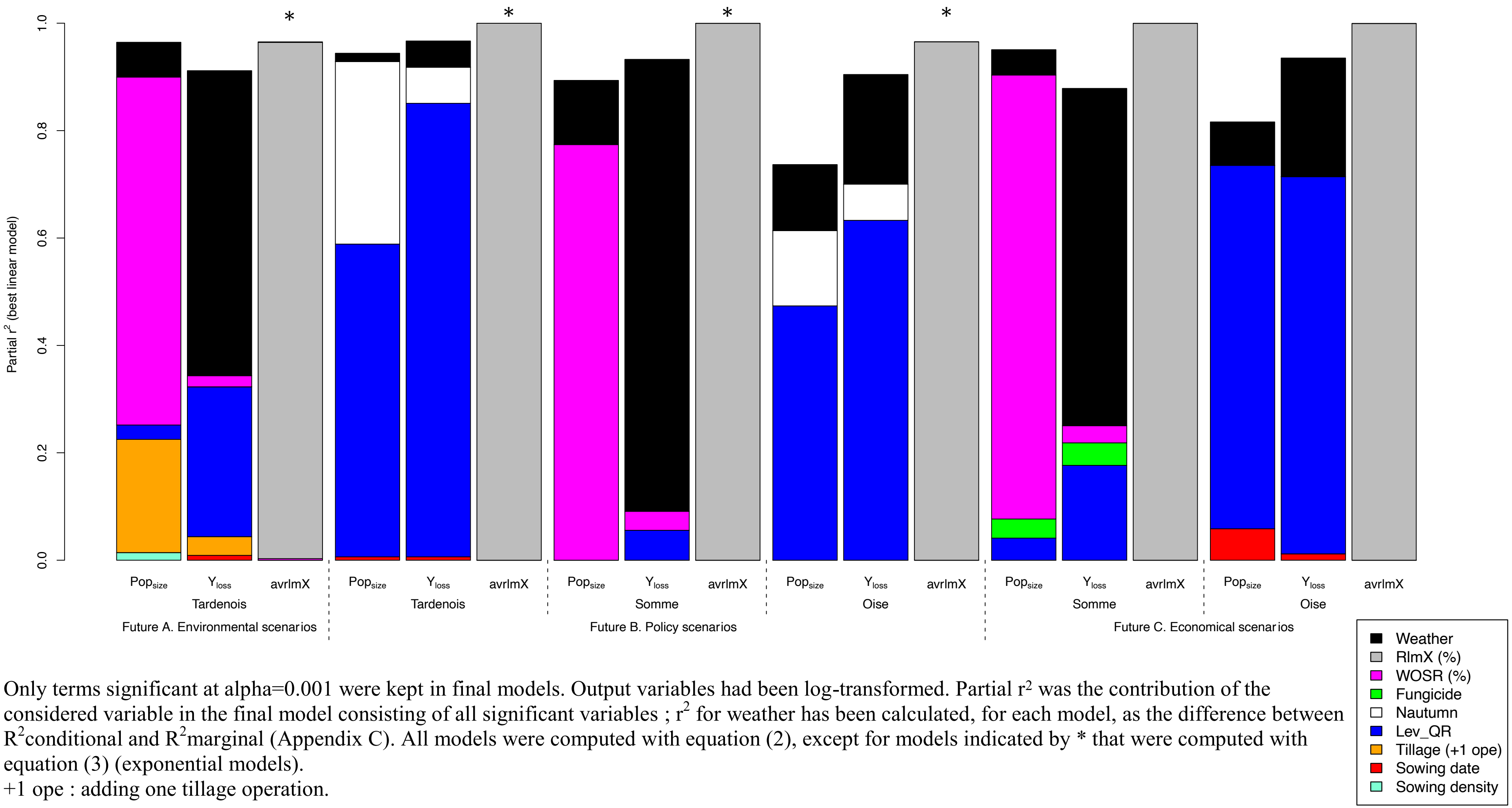
Figure 6. Final model contributions (partial r^2) of future scenarios' cropping practices to the three evaluation criteria (Pop_{size}, Y_{loss} and avrlmX) for each sub-region and future.



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^2conditional and R^2marginal (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

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

	Reference scenarios			Futures		
Sub-region	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

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.

		Environmental scenarios	Policy scenarios			Economic scenario	
Effect of…	On log(…)[a]	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]		*0.991*[c,d]				-0.016	-0.012
An increase of 1% of RlmX-cultivars[d]		*0.935*[c,d]	*0.818*[c,d]	*0.643*[c,d]	*0.815*[c,d]	2.463	1.025

[a]Output variables have been log-transformed. [b]random effect of weather on intercept only. All models were linear (Equation 2) except [c] (exponential models, Equation 3). [d]For 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.