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A bioeconomic model of downy mildew damage on grapevine for evaluation of control strategies

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ABSTRACT

In order to reduce pesticide use in vineyards, we propose a bioeconomic model to evaluate different fungicide treatment strategies. This model estimates the development of the downy mildew *Plasmopara viticola* for a given year's weather on a grapevine plot, and predicts the damage done, the yield loss, and the resulting partial gross margin, depending on the chosen protection strategy.

Grapevine growth and phenology are simulated with the STICS grapevine crop model according to the year's weather; fungal components quantify downy mildew development; damage onto leaves and fruits is characterized as a percent reduction of potential leaf area and yield; the effect of fungicide treatments is simulated as a partial protection against infection; the economic result is calculated at plot level, taking into account simulated yield, local economic conditions and costs of observations and sprayings.

The model parameters were estimated using three sets of experimental data from vineyards in the French wine-growing region of Bordeaux. Using these parameter values, the model was used to evaluate the following five protection strategies: 3 systematic fungicide spraying strategies with 2-, 3- or 4-week intervals, the "Mildium" adaptive strategy, which includes field observations and decision rules, and a control untreated strategy. Yield losses and the resulting partial gross margins were calculated for 23 annual weather examples for each strategy and the statistics of these strategies were compared. The adaptive strategy was found to be slightly less protective on average against downy mildew than the 2-week systematic spray strategy. However its low variability ensures sustainability in terms of grower's income, while reducing by one third the number of sprayings. The model hypotheses and simulation results are discussed, in relation to the particular economic context of the "Bordeaux" protected designation of origin with the objective of reducing pesticide use in vineyards.

1. Introduction

European viticulture employs a large amount of agrochemicals, which are mainly applied for controlling fungal diseases (Eurostat, 2007). Gessler et al. (2011) have thoroughly reviewed the existing literature on *Plasmopara viticola*, which is the fungus that causes downy mildew, as well as its spread and importance in the world, including Europe. All French vineyards are protected against this disease, mainly through the use of chemicals. In 2006, the mean fungicide TFI (treatment frequency index) for French vineyards was 10.8, and it varied from 5 to 20 depending on the vine-growing region. Fungicides were mainly dedicated to the control of downy and powdery mildew. The mean number of treatments against *Botrytis* is less than one per year (Butault et al., 2008). The cost of chemicals and the social demand for more sustainable and

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environmentally-friendly agriculture justify the need for tools to help reduce pesticide use in viticulture, for example through the implementation of new disease control strategies. In order to induce changes to grower's plant protection practices, it is important to evaluate the economic aspects different strategies and help to preserve the grower's income. Tradeoffs must therefore be made between a reduction in pesticide use and the minimization of yield losses. Since Van der Plank (1960, 1963), mathematical models have been recognized as valuable tools for this purpose (Teng et al., 1978; Shtienberg, 2000; Contreras-Medina et al., 2009). Simulation models are particularly suitable for seeking agronomic solutions that fulfill several objectives, such as production objectives and environmental concerns within a given cropping system (Ripoche et al., 2010, 2011). Models can be useful tools to evaluate the risks of adopting innovative treatment strategies. Ona application of this type of modeling is to contrast the "Mildium" strategy that was developed by INRA Bordeaux (France) (Delière et al., 2009) with traditional scheduled treatment strategies. To be successful, such a model would need (1) to quantify the epidemics of downy mildew in a given vineyard, depending on the year's weather conditions, (2) to simulate the grapevine development during this year and calculate its potential yield in the absence of disease and (3) to combine both data in order to get estimates of the yield loss that results from this disease under various protection strategies. These outputs may then be used to calculate the economic result of a given strategy for any year in the studied vineyard.

Several models have been proposed to describe and quantify the grapevine epidemics. Most of them concentrate on the pathogen cycle, or just a part of it. This type of information cannot be used directly to estimate the relative values of different pathogen control strategies. In order to do so, one needs not only to model the pathogen's development but also the damage that is done to the crop and the protection that is assured by the control methods under evaluation. Since the 1960s there have been many attempts to model fungal disease damage and its effects on crop yields, but grapevine diseases have not been represented (Van der Plank, 1963). For example, Teng et al. (1979) compared several yield loss estimating models for leaf rust on barley in New Zealand and they emphasized the fact that a model should be chosen to correctly describe the mechanisms involved, but also according to its intended use. Therefore, they recommended models that varied from simulation of crop loss at a regional scale to simulations intended to influence management strategies. Madden et al. (1981) compiled several studies to build a general statistical model of crop loss due to plant diseases, the simplicity of which allowed for a comparison of losses due to different diseases. However, their model does not quantify disease effects, which would be necessary to examine the effects of annual weather series on the value of different control strategies. Rosa et al. (1995) developed PLASMO software in the 1990s, which simulates downy mildew development.

Several crop growth models were designed to simulate crop yield under different circumstances and under the influence of different stresses, but they rarely included the effects of plant diseases. For example, the generic crop model STICS (Brisson et al., 2003), which has been adapted for grapevine simulation (Valdés-Gómez et al., 2009), has been used to simulate the influence of soil management (Brisson et al., 1998), water regimes (Bruckler et al., 2000; Debaeke, 2004) and changes in local or global climate (Courault and Ruget, 2001; Juin et al., 2004; Gonzalez-Camacho et al., 2008), but no components are included to account for pests or diseases. The DSSAT cropping system model (CSM) (Jones et al., 2003), which includes CROPSIM–CERES (Hunt and Pararajasingham, 1995) and CROPGRO modules (Boote et al., 1998), was adapted to include a pest module by Batchelor et al. (1993). This module allows users to input field observations of pest damage or disease severity to simulate their effects on growth and crop yield (Naab et al., 2004; Timsina et al., 2007). However the development of the disease itself was not simulated, and no module was proposed to adapt these models to grapevine simulations. Boote et al. (2008) advocated for the value of linking dynamic disease simulation models with CROPGRO to predict the effect of the disease on groundnut production. The widely used crop simulation model APSIM (McCown et al., 1995) includes grapevine among the crops that it can simulate. The effects of irrigation, nitrate availability and climate change are within the scope of this model, but not the yield reduction due to diseases or pests (Wang et al., 2004).

The link between disease dynamics and yield reduction was mechanistically quantified through different models in the 2000s, but none of them addressed this link in grapevine. For example, some complex models on the yield effects of multiple pests and diseases, such as RICEPEST in rice (Willocquet et al., 2000, 2002; 2004) or WHEATPEST in wheat (Willocquet et al., 2008), described and simulated crop yield reductions that result from a certain level of disease severity and pest infestation, but the disease development that produces this severity has to be quantified by other means. Even if they were adapted to grapevine, these models would not allow us to simulate overall disease development, the effect of control strategies and the resulting yield loss.

The goal of the present research was to simulate the development of downy mildew on a grapevine plot, along with the damage caused by this disease and the effects of several crop protection strategies on relative yield loss, in a model integrating agronomic, pathological and economic aspects. The objective of this model was to compare the effects of different grapevine protection strategies on the grower's income. The structure of the disease development model was built from existing knowledge (Blaise and Gessler, 1992; Gessler and Blaise, 1992; Calonnec et al., 2008). The model requires annual weather records of the studied year (temperature and rainfall, hereafter named "weather pattern") to simulate both potential grape yield and downy mildew development. Model parameters values were either found in the literature or estimated with a three-year data set. The parameterized model was then used to simulate the damage and yield loss resulting from different grapevine downy mildew control strategies for a set of 23 years. Frequencies of yield loss and economic results obtained in the different climate/strategy combinations were analyzed and discussed in terms of tradeoffs between pesticide use reduction and a need to preserve grower's income, depending on the agro-economic context. The control strategies that were evaluated in this example included either systematic treatments at fixed time intervals or adaptive strategies such as "Mildium", based on field observations of disease development used to modulate treatment decisions (Delière et al., 2009; Léger et al., 2007).

2. Materials and methods

2.1. The model structure

The model includes five components (Fig. 1): (1) the grapevine growth and development, as characterized by phenological stages, LAI and potential yield; (2) the different stages of fungal development on the plant; (3) the effects of plant protection strategies; (4) the damage to leaves and berries as caused by the fungal infection; and (5) the economic results. The protection strategies were simulated for a set of weather scenarios, and the results were expressed as differences in partial gross margin, to best estimate the economic risk and feasibility of each strategy.

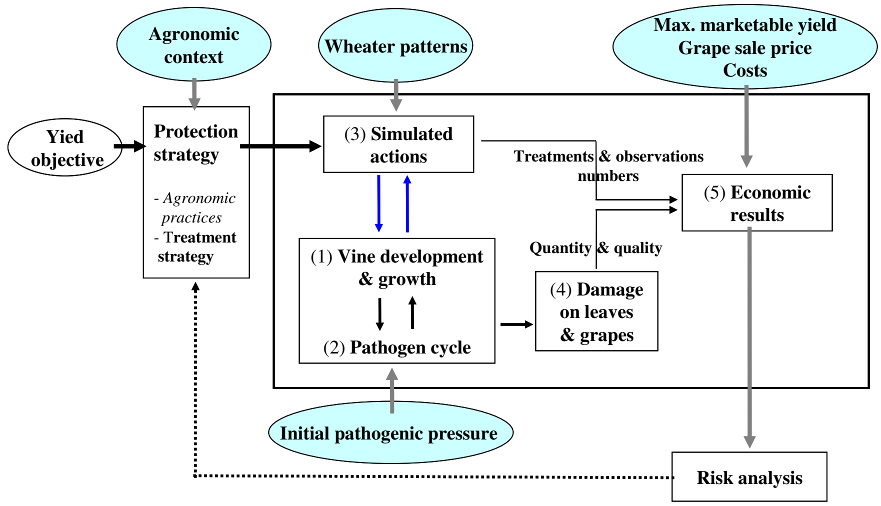

Fig. 1. Schematic representation of the structure of a bioeconomic model of downy mildew damages to grapevine.

2.1.1. *Grapevine growth and development*

For our purposes, the grapevine module of the STICS crop model (García de Cortazar-Atauri, 2006; Valdés-Gómez et al., 2009) was used to simulate the vineyard, which was characterized by its leaf area per soil unit, phenology, and the change in potential yield throughout the growing season in the absence of disease. The time step for this model was a day.

To model the disease development in leaves, the total leaf area within the vineyard at time t was divided into four mutually exclusive portions (Eq. (1)):

$$LA_T(t) = LA_I(t) + LA_R(t) + LA_P(t,d) + LA_S(t) \quad (1)$$

where $LA_T(t)$ represents the total leaf area, $LA_I(t)$ is the infected leaf area, $LA_R(t)$ is the leaf area that has reached the age when leaf tissues become resistant; $LA_P(t,d)$ is the leaf area that is protected from infection by a fungicide treatment sprayed on day d and $LA_S(t)$ is the remaining leaf area, which is not resistant, infected nor protected by chemicals, and is therefore susceptible to infection by downy mildew.

The development of the fungus on the plant and the effect of fungicide treatments determined the changes in partitioning between leaf area compartments from day to day. However, the grapevine development and potential growth were simulated independently from the disease dynamics, and the damage by the pathogen to leaves and fruits due to the pathogen were estimated without any feedback effects such as vine growth compensation. The development of the disease allowed us to calculate a reduction factor for the potential yield, which was calculated on the assumption of no disease.

2.1.2. *Disease development*

2.1.2.1. Primary infections. At the beginning of the vegetative season, the grapevine is exposed to primary infections. These represent new infections in the observed field, that originate either in sporangia coming from outside the grapevine plot under study, or from oospores that were preserved on plant parts in the soil. Primary infections are essential for the initialization of disease epidemics, but they are quite difficult to predict because they result from several processes that take place from the previous autumn through the winter and spring. Oospores form within infected tissues at the end of the vegetative season, and maturation takes place during over-wintering in the leaf litter or the soil. Spore dispersal and germination are under the control of several factors, mainly having to do with the weather.

Although several attempts have been made to model and predict primary infections (Rossi et al., 2008), including a precise prediction of this developmental step in our model would have added considerable complexity. We therefore chose to adopt a simplified way of simulating this phenomenon.

The results of primary infections were simulated as the infection of a determined area infected on each day as soon as all conditions were met (Fig. 2). First, the plant had to be within a susceptible developmental stage; this period was bounded by the PI_{begin} and PI_{end}. Within this period, the weather conditions necessary for enabling primary infections were: a certain amount of rain allowing germination of oospores and splashing of spore-containing droplets, and a temperature that allows infection. The thresholds for rain and average daily temperature were $PI_{minrain}$ and $PI_{mintemp}$.

When these conditions were met, and as long as a maximal number of possible primary infections, or PI_{maxnb}, was not reached, the infected leaf area increased daily by PI_{area} (Eq. (2)). This last parameter characterizes the newly infected leaf area at each favorable occurrence and can be considered as an indicator of the primary infection pressure by downy mildew under given weather and crop conditions. Therefore, all primary infections produced equal areas of infected leaf, and they can occur throughout the season, as stated by Kennelly et al. (2007a) and Vercesi et al. (2010).

$$\begin{aligned}
&\Delta\, LA_I^P(t) = PI_{area} \\
&\text{if} \quad Stage(t) \geq PI_{begin} \quad \text{and} \quad Stage(t) < PI_{end} \\
&\qquad \text{and } Rain(t) \geq PI_{minrain} \\
&\qquad \text{and } Tmean(t) \geq PI_{mintemp} \\
&\qquad \text{and } PI_{nb}(t-1) < PI_{maxnb} \\
&\text{else } \Delta\, LA_I^P(t) = 0
\end{aligned} \quad (2)$$

2.1.2.2. Sporulating areas. Grapevine pathogen development follows different steps. After germination, the germ tubes of the pathogen penetrate the plant cuticle, and the disease goes through a latent period during which the mycelium grows inside the leaves but no symptoms appear. The duration of this phase (parameter *latency*) is controlled by temperature and is simulated using the methods of Blaise and Gessler (1992) and Calonnec et al. (2008).

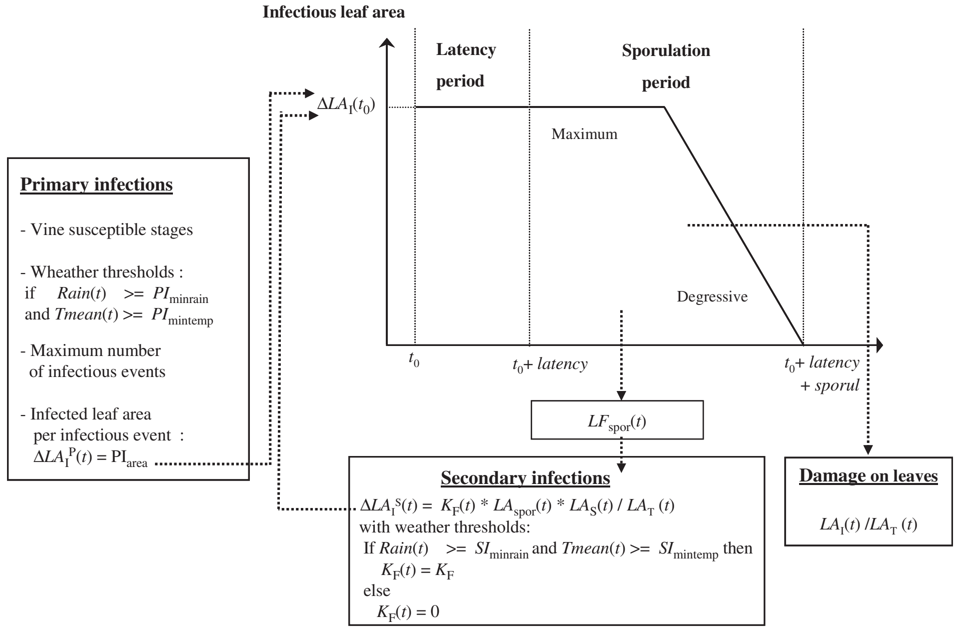

Fig. 2. Sporulation *vs*. time functions for primary and secondary leaf infections, as represented in the simulation model.

At the end of latency, the hyphae grow outside the leaf surface, and produce spore-bearing organs; the spores are released into the environment and extend the infected area through secondary infections. The sporulating area $LA_{spor}(t)$ is calculated for each day, assuming that all contaminated areas are able to sporulate completely as soon as the latent period has ended and during a period of constant sporulation, and after that, the sporulation decreases linearly, depending on parameter sp_{triang}, until the leaf becomes non-infectious (Fig. 2). The total duration of spore production in an infected area is called *sporul*.

2.1.2.3. Leaf secondary infections. Secondary infections occur when spores from a sporulating leaf surface develop a new disease spot on a susceptible leaf. This mechanism and its regulation by microclimatic factors were simulated according to the methods of Gessler and Blaise (1992).

We assumed that the only climatic requirement for this process is the presence of liquid water, which is necessary for spore germination on the leaf surface, and that this water comes from rainfall; we defined the minimal amounts of rain and temperature that allow this mechanism as $SI_{minrain}$ and $SI_{mintemp}$. When these conditions were fulfilled, the probability for an infectious spore to germinate on a susceptible leaf area was assumed to be equal to the proportion of susceptible leaf surface within the total leaf area. The amount of newly infected leaf area that was produced by this infectious event is determined by parameter K_L (Fig. 2). Parameter K_L can therefore be described as the infection power of the sporulating areas towards healthy susceptible leaf area.

The new infected area per day at time *t* that results from secondary infections could therefore be calculated as:

$$\begin{aligned} \Delta LA_I^S(t) &= K_L(t) * LA_{spor}(t) * LA_S(t) / LA_T(t) \\ \text{with} \quad & \text{if } Rain(t) \geq SI_{minrain}, \text{ and } Tmean(t) \geq SI_{mintemp} \\ & \text{then } K_L(t) = K_L \\ & \text{else } K_L(t) = 0 \end{aligned} \tag{3}$$

At each time step *t*, the increase in infected leaf area was computed as the sum of the new primary and secondary infections: $\Delta LA_I(t) = \Delta LA_I^P(t) + \Delta LA_I^S(t)$. The increase in infected leaf area take the form of a logistic-like curve, where $K_L(t)$ is the relative growth coefficient (analogous to *r* in a standard logistic equation), $LA_{spor}(t)$ is the "driver" of the growth (analogous to N) and $LA_S(t)/LA_T(t)$ is the "limiter" of the growth curve (analogous to 1 − N/K).

2.1.2.4. Ontogenic resistance. We defined parameter *resist* as the age of ontogenic resistance, which is when leaves that have not been infected lose their susceptibility to the pathogen. At each time step *t*, the part of the leaf area without infection becomes resistant to infection upon reaching the age of *resist*, and is then subtracted from the susceptible leaf area.

The calculation of the resistant leaf area was computed with a daily algorithm. The susceptible leaf area was subdivided into age classes and the probability of each new infectious event occurring on a leaf surface of age *n* only depends on the portion of leaf surface of age *n* within the total susceptible leaf area.

2.1.2.5. Protection by fungicide. The control of fungal development by pesticide applications depends on the efficacy of the chemical and the persistence of the fungicide in the canopy. For this model, we only considered the protective effect of chemical treatments on healthy susceptible plant parts, and did not account for any effect on incubating infected leaves (curative efficacy) or anti-sporulant activity. Furthermore, organs that appeared after a treatment did not get any protection.

The protective effect was then characterized by three parameters: the rate of protection $chem_{effic}$ (between 0 and 1) including the product efficacy and spraying characteristics such as the canopy coverage and dose. The protection remained equal to $chem_{effic}$ during $chem_{life1}$ days and then declined in a linear fashion (see Latin, 2006), reaching zero in $chem_{life2}$ days. A leaf that received a chemical spray on day *d* therefore lost all protection after day $d + chem_{life1} + chem_{life2}$. The leaf area that was protected at time step *t* by a fungicide treatment sprayed on day *d* was expressed as $LA_P(t,d)$.

2.1.3. Damage and yield loss

An early infection of the grapevine may cause the loss of grapes and berries, whereas infections occurring after flowering will essentially cause berry losses and no grape decay. In both cases, the hypothesis was that these infections are caused by spores moving from sporulating leaf surfaces, whose area was $LA_{spor}(t)$. The sporulating leaf surface was used as an indicator of the pathogen pressure on reproductive parts. The infective potential of these surfaces was K_{early} towards young reproductive organs before flowering and K_{late} after flowering. The climatic determinism of K_{early} and K_{late} was the same as K_L. The progression of infection on grapes and berries depended also on the susceptibility of these organs (functions $Susc_{early}(t)$ and $Susc_{late}(t)$) and was reduced by their relative rates of protection by fungicides. The proportions of grapes and berries protected at time step t by a fungicide treatment sprayed on day d were expressed as $Prot_{early}(t,d)$ for young organs before flowering and $Prot_{late}(t,d)$ for grapes and berries after flowering, with the same parameters than for leaves.

Our model estimates the quantity of clusters and berries that were lost due to fungal infection. The total expected yield loss was the combined effect on the potential yield of early and late infections, depending on whether they occur before or after flowering. An early infection of the grapevine may cause the loss of a certain number of clusters and berries, whereas infections occurring after flowering will essentially cause berry losses and no cluster decay. The hypothesis for both cases was that these infections were caused by spores moving from sporulating leaf surfaces, whose area was $LA_{spor}(t)$. The sporulating leaf surface was used as an indicator of pathogen pressure on reproductive parts. The infective potential of these surfaces was K_{early} in young reproductive organs before flowering and K_{late} after flowering. The climatic determinism of K_{early} and K_{late} was the same as in K_L. The progression of infection in clusters and berries also depended on the susceptibility of these organs (functions $Susc_{early}(t)$ and $Susc_{late}(t)$) and was reduced by relative rates of fungicidal protection. The proportion of clusters and berries that was protected at time step t by a fungicidal treatment that was sprayed on day d was expressed as $Prot_{early}(t,d)$ for young organs before flowering and $Prot_{late}(t,d)$ after flowering, with the same parameters as in the leaves.

2.1.3.1. Early damage to clusters and berries. The fraction of susceptible reproductive organs evolves with time, depending on the variable $g_{pot}(t)$; $g_{pot}(t)$ represents the number of organs that the fungus can infect at time t, divided by the total number of organs that will be present at flowering if the fungal disease does not suppress any of them; its range is between 0 and 1. The rating is 0 until an early stage of growth when the clusters and berries begin to form and are accessible to the pathogen, and it shows a linear increase from 0 to 1 at flowering time. Its increase ratio is $\Delta g_{pot}(t)/g_{pot}(t-1)$. At time t, the actual fraction of susceptible organs, accounting for the effects of the plant disease, is $g(t)$. The susceptibility of young clusters and berries to fungal infection ($Susc_{early}(t)$) is assumed to be 1 until flowering, and 0 afterwards.

The loss of clusters and berries at time t depends on the healthy portion of young clusters and berries on the plant at previous time step $g(t-1)$, the infection capacity of the pathogen, the susceptibility of these organs and the function of protection by chemical treatments :

$$\Delta g_{loss}(t) = g(t-1)*\left[K_{early}*LA_{spor}(t)\right]*Susc_{early}(t) *\left[1-Prot_{early}(t,d)\right] \quad (4)$$

and the actual portion of healthy young clusters and berries at time t, $g(t)$, is therefore:

$$g(t) = g(t-1)*\left(1+\Delta g_{pot}(t)/\Delta g_{pot}(t-1)\right) - \Delta g_{loss}(t) \quad (5)$$

At flowering, the actual percentage of healthy clusters and berries reaches the value: $G = g(flowering)$.

2.1.3.2. Damage to berries after flowering. The potential yield of the crop without any pathogen infection was $y_{pot}(t)$, as expressed as the weight of berries per ha (in tons per ha); it could lead to an actual yield at harvest day of $y_{pot}(harvest)$. The function y_{pot} was simulated by STICS, and the berry damage was expressed as a loss of potential yield $y_{loss}(t)$.

At every time step, we calculated $y_{loss}(t)$ using Eq. (6), in which the reduction in yield at time t was a portion of the weight of healthy berries that were accumulated at time $t-1$ and depended on the infection capacity of the pathogen, the function of susceptibility and the function of protection by chemical treatments:

$$\Delta y_{loss}(t) = y(t-1)*\left[K_{late}(t)*LA_{spor}(t)\right]*Susc_{late}(t) *[1-Prot_{late}(t,d)] \quad (6)$$

The actual quantity of berries at time t, taking into account the amount loss due to *P. viticola*, could be expressed as:

$$y(t) = y(t-1)*\left[1+\Delta y_{pot}(t)/y_{pot}(t-1)\right] - \Delta y_{loss}(t) \quad (7)$$

where

$$y(t_0) = G*y_{pot}(t_0) - \Delta y_{loss}(t_0),$$

where t_0 is the first day when $y_{pot}(t_0-1)=0$ and $y_{pot}(t_0)>0$.

The susceptibility function of berries to fungal infection was similar to what was proposed by Gadoury et al. (2003): $Susc_{late}(t) = 1$ from the "flowering" stage onwards. Susceptibility was constant during a certain period, and then decreased in a linear way to 0 after one to a few weeks (Ficke et al., 2004). The duration of both constant and decline periods could be adjusted.

2.1.4. Plant protection strategies

Farmer strategies for protecting grapevines against downy mildew were represented as decision rules. Based on these rules and accounting for each year's weather and plant-pathogen development, our model generated operational schedules for each combination of strategic choice and weather pattern. These operations could be fungicide sprays or field monitoring of mildew symptoms for adaptive control strategies such as "Mildium". The "Mildium" strategy is a compromise that aims to reduce the number of sprayings through better supervision of disease progress during the season. It combines "mandatory" treatments to protect highly susceptible grapevine stages and field observations at key stages, which help to postpone or eliminate one or several "optional" sprayings (for a full description of this decision support system, see Delière et al., 2009; Léger, 2008; Léger et al., 2008, 2010).

2.1.5. Economic impacts

To estimate the economic impacts of the downy mildew depending on the control strategy, we used as an indicator the margin per ha (yield/ha*price – costs/ha) calculated on the studied vine plot, for each plant protection strategy and each climatic year.

For each plant control strategy (st) and annual weather pattern (y), the disease development part of the model calculated the current yield per ha ($Y(st,y)$) as a fraction of the potential yield per ha expected on year y at the plot level in the absence of disease ($Y_{pot}(y)$), with $Y_{pot}(y) = y_{pot}(harvest)$ and $Y(st,y) = y(harvest)$ for the strategy and climatic year of interest (see 2.1.3).

The potential yield ($Y_{pot\_STICS}(y)$) was computed each year by STICS. However, based on preliminary experiments and in order to take into account all random effect that were not otherwise included, we applied a 20% reduction to the potential yield that was calculated by STICS, where $Y_{pot}(y) = 0.8*Y_{pot\_STICS}(y)$.

The vineyard under study was operated in the economic context of a protected designation of origin that fixes an upper bound (Y_{max}) to the marketable yield per ha for each plot and year; the marketable yield of a given plot is then:

$$Y_{mark}(st,y) = \min(Y_{max}, Y(st,y)) \quad (8)$$

This maximal marketable yield per plot has a large effect on the economic results of the strategies that are under evaluation. Specifically, if the potential yield is greater than this maximal level and if a given strategy keeps the yield loss from the disease to a sufficiently low value, there is no effect on the marketable yield. On the other hand if the potential yield is lower than this upper bound, all yield losses will affect the marketable yield and all protection strategies affect the partial gross margin.

After harvest, the grapes are sold to wine-producing operators (cooperatives etc.) at a price (p) that is fixed by these operators; this price may vary according to the quality of the crop. To account for this crop quality loss from downy mildew, we introduced a rate of reduction (r_P) applied the price that is paid to the grower if the sanitary state of the crop is lower than a threshold (r_D). As a simplification, we used the percentage yield loss as an indicator of this sanitary state. The price *P(st,y)* paid to the grower for control strategy *st* and year *y* was expressed as follows:

$$\begin{aligned} &\text{If} \quad Y(st,y)/Y_{pot}(y) < r_D, \quad P(st,y) = p \\ &\text{else} \qquad\qquad\qquad\qquad\quad P(st,y) = r_P{*}p \end{aligned} \quad (9)$$

Therefore the current gross product (marketable yield*price) for a control strategy and a given weather pattern was:

$$GP(st,y) = Y_{mark}(st,y){*}P(st,y) \quad (10)$$

Costs included in the margin calculation were:

(1) the total cost of fungicide spraying, as calculated by the number of sprays $Nb_S(st,y)$ multiplied by the unit cost per spray (c_S), including pesticide cost and cost-in-use of the equipment and labor;
(2) the total cost of field observations, when applicable, as calculated by the number of observations $Nb_O(st,y)$ multiplied by the unit cost of an observation (c_O), which consists in labor costs only.

The cost per ha of any protection strategy is therefore expressed as follows:

$$C(st,y) = Nb_S(st,y){*}c_S + Nb_O(st,y){*}c_O \quad (11)$$

Because all the other costs will be the same regardless of the control strategy, we did not include any of them, because our goal was to compare grower's choices in terms of protection strategy. The partial margin, chosen as an indicator to compare the results of these strategies, only included spraying and observation costs.

The partial margin per ha, for each strategy and year, was therefore:

$$M(st,y) = GP(st,y) - C(st,y) \quad (12)$$

2.2. Parameter estimation

The parameter values that describe the disease development elements for this model are rarely found in the literature, except for the latent period, which was described by Gessler and Blaise (1992). These parameters were therefore estimated from three sets of observational data that were collected by the Institut Français de la Vigne et du Vin (IFV) from two vineyards (cv. Merlot) located in Salleboeuf (44°84 N, 0°39′ E) and Pompignac (44°85 N, 0°44′ E), which were grown without any fungicidal treatments in 2006, 2007 and 2008 in the Bordeaux wine region. The year 2006 was characterized by a relatively low pathogen pressure, whereas the weather during 2007 and 2008 was favorable for fungal development, producing a high downy mildew pressure on the vines.

Weather data were collected by meteorological data loggers near each vineyard. These data described rainfall events with an appropriate level of accuracy on a local scale, which is important because the availability of liquid water is necessary for *P. viticola* development.

A set of parameter values was sought that combined a low RMSE (root mean square error) between the observed and simulated values of damage on leaves ($RMSE_L$) and yield loss ($RMSE_Y$) and realistic values for all parameters.

The field and simulated data comparison required some adjustments. The model simulates the day when a lesion on a leaf or berry was created; to know the time when it appeared in the field, we needed to add the incubation time, which we considered equal to the latency for this purpose. Disease severity on leaves was estimated as the percentage of infected leaf surface; on berries, the severity was calculated as the proportion of yield lost because of the disease:

$$Sever_L(t) = LA_I(t)/LA_T(t) \text{ and } \mathrm{Sever}_Y(t) = 1 - y(t)/y_{pot}(t) \quad (13)$$

2.3. Evaluation of strategies of grapevine protection

Our model was used to evaluate the results of four different pathogen control strategies and their effects on disease development and yield loss. Disease development was simulated for this purpose in a Merlot vineyard over the 1988–2010 period, using actual weather data collected at La Ferrade, which is near Bordeaux (44°47′ N, 0°34′ W).

Model parameter values were those obtained previously, and the initial primary infection level PI_{area} was set equal to $4{*}10^{-7}$ (as expressed in ha of leaf area per ha of vineyard). This value was chosen because it corresponds to an average value of parameter estimates of the PI_{area} (Table 1), and therefore can be considered to be somewhat representative of what initial infection level may be in the region of interest.

The control strategies under evaluation were (1–3) three "regular spraying" strategies, which consisted in planned fungicide sprays every 14, 21 or 28 days. Sprayings began when the vine had 6 leaves and ran until one week after the ripening stage; (4) the application of the "Mildium" decision rule, with a minimum delay of 12 days between sprayings (Delière et al., 2009; Leger, 2008) and (5) a strategy with no fungicide application, which was the control.

The phenology, development of grapevine leaf area and potential yield were simulated using STICS. Fungicide spray efficacy was simulated as a having 90% protective effect on leaves ($chem_{effic}$)

Table 1
Estimated day of first primary infection, number of primary infections and sizes of individual infection (*PI_area*) on three data sets of *P. viticola* development related to three year/location combinations within the Bordeaux region, France.

	Day of first infection	Number of primary infections	*PI*-area
Salleboeuf 2006	2 days after "2 leaves" (27/04)	4	4.5 e-7
Pompignac 2007	4 days after "6 leaves" (30/04)	2	3.5 e-7
Pompignac 2008	"2 leaves" (29/04)	8	4.0 e-7

over the course of 16 days, including 12 days with maximal efficacy ($chem_{life1}$) and with a decrease during the next 4 days ($chem_{life2}$). The protective functions on grapes and berries before ($Prot_{early}$) and after flowering ($Prot_{late}$) were defined in a similar manner using the same parameter values.

For each strategy under evaluation, the model produced estimates of several key variables such as the severity of leaf damage, relative yield loss and economic results. These values were collected for all the tested weather patterns, allowing a frequency analysis of these results. Control strategies were compared for the whole set of 23 weather patterns using the mean, median and 1st and 3rd quartiles for each variable.

The study vineyards were located within the "Bordeaux" designation of origin in south-western France. The registered maximal yield (Y_{max}) for this designation is 8 tons of grapes (60 hL of wine) per ha. The sale price of grapes for this wine type is 600 €/t, which results in a potential gross product of 4800 euros per ha. We fixed the cost of a single spraying at 70 euros per ha, including 32 euros for the fungicide. On the basis of observations conducted when testing the "Mildium" strategy in vineyards, the cost of a one hectare field observation for this strategy was assumed to be 80 euros, which is for labor only. This cost may vary depending on the structure and heterogeneity of the vineyards, the training of observers, etc., and can easily be modified within the model.

3. Results

3.1. Parameter estimation

Comparisons between simulated and observed damage to leaves and fruit were used to estimate parameter values for the disease simulator, as presented in Fig. 3. Because disease severity was visually estimated only once a week, there is some uncertainty about the exact day of appearance of the symptoms. this uncertainty is represented in our results by an "x-axis" uncertainty interval on graphs of severity versus time; the horizontal interval before each observed data value therefore represents the period that is likely to include the symptom onset date. The uncertainty about the severity itself is represented by a "y-axis" interval to account for the differences in training among observers.

The parameter estimation was intended to produce values that would result in a good fit to the observed damage on leaves and fruit, but priority was given to yield loss simulation, because the aim was to evaluate the impact of the disease control strategy on the final product.

The model parameters values were fitted as follows:

(1) the period of grapevine susceptibility to primary infection was delimited as follows: it began (PI_{begin}) when the vine had two emerged leaves and ended (PI_{end}) at 50% bloom; the number of days needed to reach these phenological stages was calculated by using a vineyard simulation in STICS; the maximal number of primary infections was unlimited: $PI_{maxnb} = \propto$;
(2) the climatic thresholds for primary infection development were $PI_{minrain} = 7$ mm, $PI_{mintemp} = 10.7$ °C; the number of primary infections and dates of first infection, which were calculated according to these thresholds in each weather pattern, were therefore year/location dependent;
(3) the newly infected leaf area at every infection event (PI_{area}) was fitted independently for each location and year to minimize RMSE;
(4) the age at which a leaf reached ontogenic resistance was $resist = 50$ days;
(5) the parameters for sporulation simulation were $sporul = 22$ days and $sp_{triang} = 0.5$;
(6) the value of the propagation of infection parameter K_L was estimated at 3.6 with thresholds $SI_{minrain} = 1.5$ mm and $SI_{mintemp} = 10.7$ °C;
(7) the parameters that accounted for disease propagation to plant reproductive organs were: $K_{early} = 7.2$ and $K_{late} = 3.6$;
(8) the evolution of grape susceptibility to infection was found to be constant and equal to 1 for 25 days after blooming, and then decreased to 0 in 40 days.

Estimates for the day of the first primary infection (which was expressed in relation to the grapevine's phenological stages), infected leaf area at each infection occurrence and number of primary infections in each of the three data sets are presented in Table 1. The primary infections were found to begin at very similar dates, but at rather different grapevine developmental stages. For example, the phenological stages in Pompignac 2007 were more advanced than in the other series presented in Fig. 3: a warm beginning of spring caused early grapevine development, but the dry conditions of this period did not allow for the development of early infections.

Comparisons between field observations and model simulations showed that it was possible to obtain a set of parameters allowing the model to simulate the development of downy mildew in three different weather pattern/location combinations, which demonstrated different climatic and epidemiological dynamics.

These situations included different disease dynamics depending on the year, which led to differences in the model's ability to accurately simulate the observed data (Fig. 3). In our examples, the real data were correctly simulated in 2007. Leaf damage was overestimated for 2008, but the final yield loss was correctly predicted; in 2006, we observed low disease development and the model was less accurate at simulating the final damage to grapes and the yield loss. This ability to predict the disease development under various weather conditions supports our assumptions about the climatic determinism of disease development that were used in our model.

3.2. Evaluation of grapevine protection strategies

3.2.1. Simulations of damage resulting from downy mildew

Because our simulator was able to predict the development and impact of downy mildew on a Bordeaux vineyard, we used it to evaluate different grapevine protection strategies over the long term. Three criteria were used to evaluate each strategy: its protective efficacy against mildew attacks on leaves and yield loss as represented by disease severity on leaves and berries, its ability to maintain the grower's income as represented by the partial gross margin, and its environmental impact as represented by the number of sprayings.

The leaf area percentage with downy mildew symptoms (severity on leaves) for the years 1988–2010 on cv. Merlot under weather conditions recorded in "La Ferrade" (Gironde, France) is plotted in Fig. 4a. Similarly, Fig. 4b shows the yield loss as a percentage of symptom-bearing grapes.

Years with high pathogenic pressure can be found easily on the graphs, because they resulted in high levels of infection in most cases (except for the most intensive control strategy). Without any treatment, more than 60% of the leaf area was infected by the disease in 14 of the 23 weather patterns under consideration. During the years that had more than 60% leaf damage, the yield loss was total (more than 85%) when adopting the untreated strategy. Only one third of the tested weather patterns would have resulted

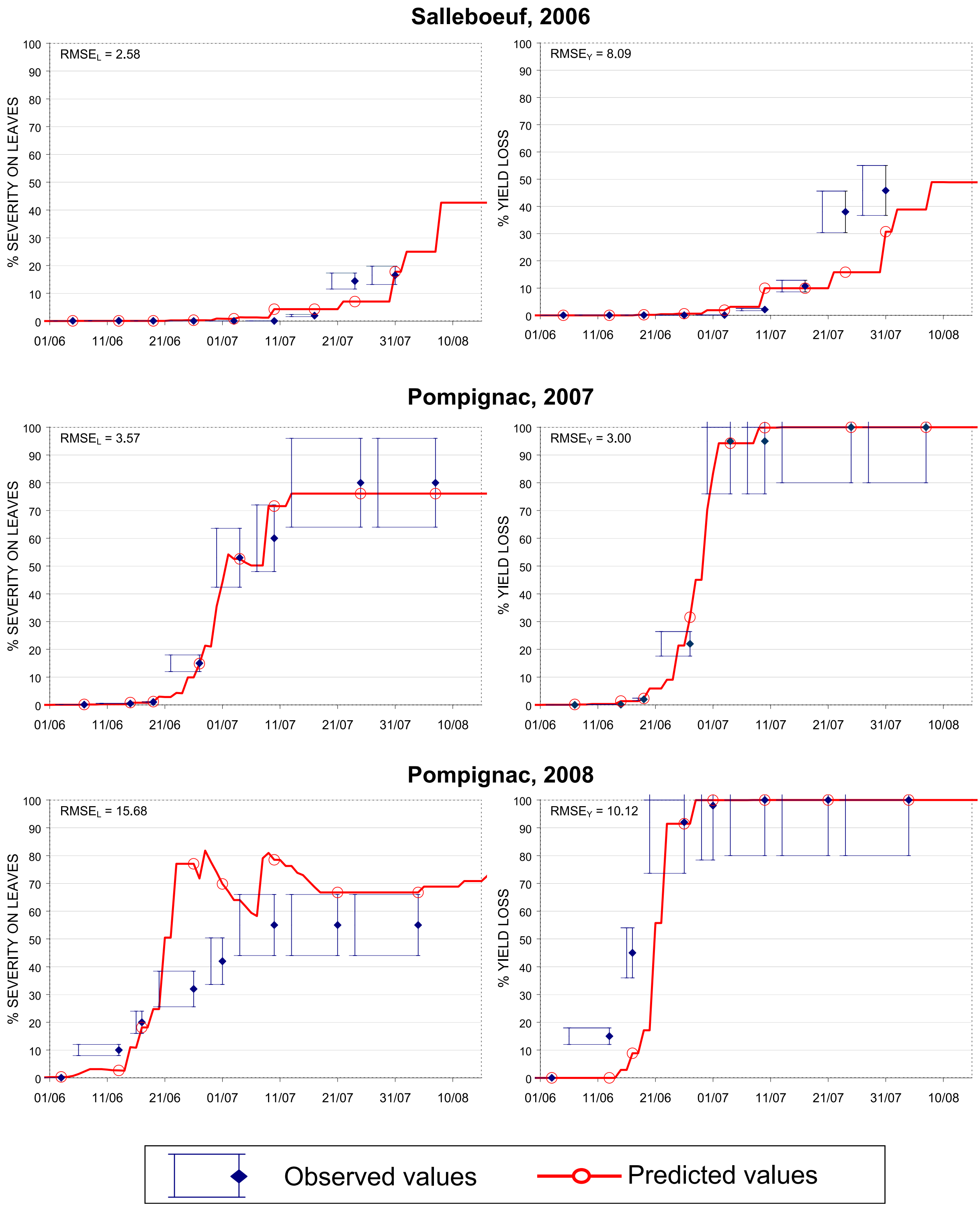

Fig. 3. Results of parameter estimation: observed *vs.* predicted development of downy mildew on vineyard plots without any chemical treatment on three year/location combinations in the Bordeaux region. From top to bottom: location Salleboeuf, year 2006; location Pompignac, year 2007; location Pompignac, year 2008. Left: damages on leaves; right: yield loss.

in a moderate level of yield reduction by downy mildew (less than 15%) without fungicide.

The most intensive disease control strategy, which consisted of spraying once every 14 days during the whole susceptible period, produced good disease control every year, with an average of 0.8% potential yield loss. The worst year for this strategy was 1999, which had a 7% infected leaf area and 3% yield loss. In this same year, the “Mildium” strategy produced a similar level of disease control.

Systematic control treatments with reduced frequency (one spraying every 21 or 28 days) led to a higher level of yield loss. The loss was higher than 20% in 9 years out of 23 with the “28 days”

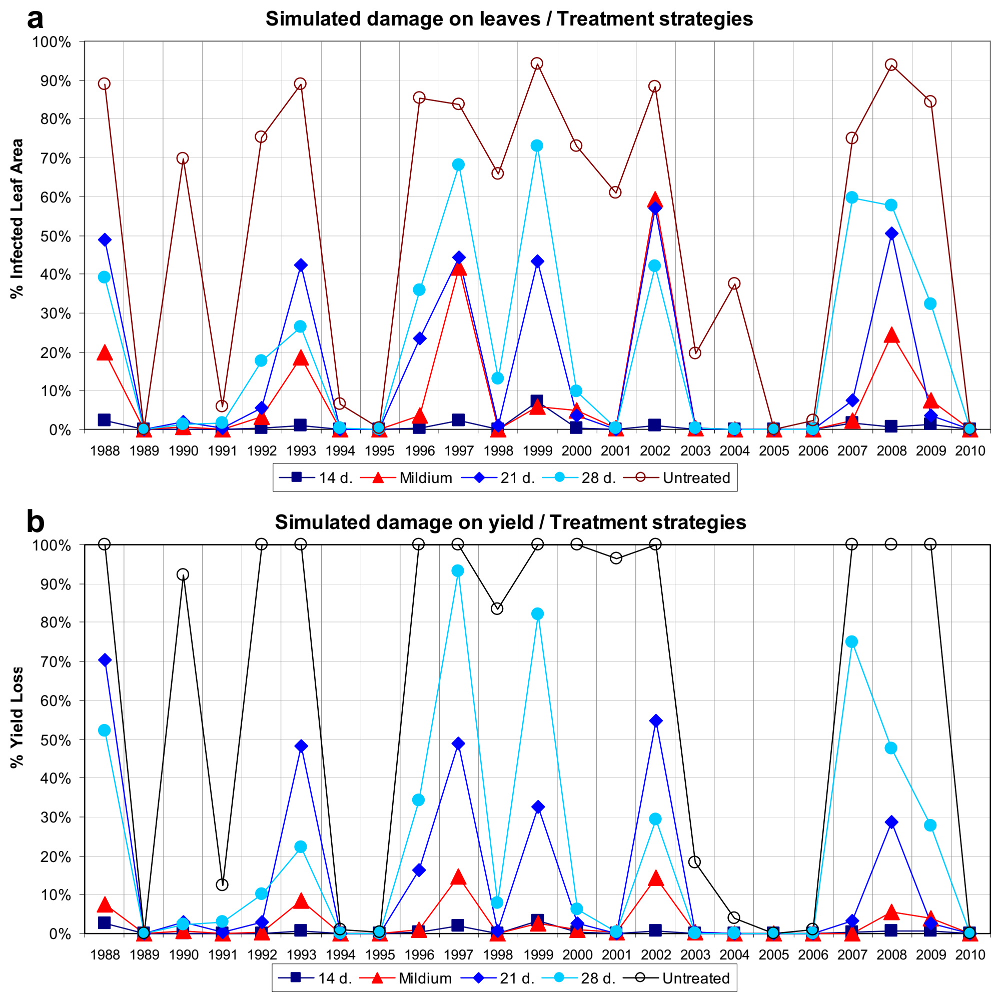

Fig. 4. Simulation of severity for downy mildew symptoms on leaves (a) and grapes (b) on a Merlot grapevine plot during years 1988 to 2010, under climatic conditions of "La Ferrade" (near Bordeaux, France), with the application of different disease control strategies.

strategy, 6 years out of 23 with the "21 days" strategy, and never with the "14 days" and "Mildium" strategies. The 10% threshold for yield reduction was reached or exceeded 0, 7, 9 and 16 times during the study period with the systematic "14 days", "21 days", "28 days" and no-treatment strategies respectively, and twice with the "Mildium" strategy.

With the "Mildium" strategy, the yield loss never exceeded 15% (average: 2.7%), and was at a maximum in 1997 and 2002, reaching 14.5%. On the grape leaves, the severity of downy mildew was more than 25% for 6 times with the "21 days" strategy and only twice with the "Mildium" strategy.

3.2.2. Number of treatments

The most intensive disease control strategy we evaluated ("14 days") is also close to the most frequently used by grapevine growers in the region of interest. This strategy was the most protective against downy mildew and naturally resulted also in the highest number of chemical treatments. The good control achieved through this intensive strategy had a high cost in term of fungicide spraying: it led to an average of 7.3 sprayings per year. As expected, systematic control treatments with reduced frequency (one spraying every 21 or 28 days) resulted in reduced numbers of fungicide sprayings (means: 5.0 and 4.0 sprayings per year, respectively). The systematic strategies resulted in very little variability in the number of treatments depending on the year: the only source of variation is the length of the period during which fungicides are sprayed, that begins at "6 leaves" stage and ends one week after ripening. This duration can be reduced on some years if climatic conditions accelerate the grapevine development. Depending on the years, the "Mildium" adaptive strategy led to a maximum of 6 sprayings during the season, with as few as two sprayings for 4 of the 23 years. The average value was 5.0 treatments, which was about one third less than the most intensive systematic control strategy.

3.2.3. Economic results

To evaluate the variability of economic results for the tested control strategies, the costs incurred should be taken into account, as well as the effects of the disease on grape yield. We determined a partial margin per hectare for each strategy and each year. This margin can be described as a synthesis of several elements (Fig. 5).

The marketable yield depends on the following factors:

(1) yield loss caused by the disease;
(2) yield cut imposed by the upper bound on marketable yield in the designation of origin of the studied region;
(3) weather patterns effects, which cause potentially yields than the previous upper bound. Fig. 5a summarizes these effects on the average marketable yield for each strategy.

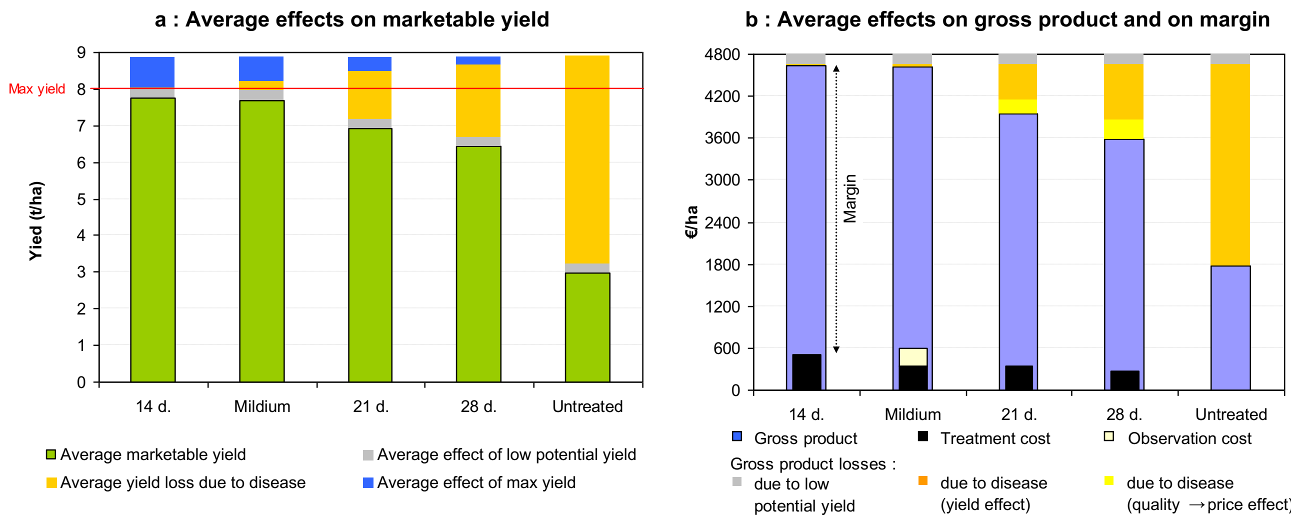

Fig. 5. Economic and agronomic components affecting grape marketable yield (a), gross product and margin (b) depending on disease control strategy.

Once the marketable yield is known, the price paid to the grower may be lowered in years with highly infected grapes. This needs to be taken into account to calculate the gross product of the vineyard plot.

Finally, the margin also depends on spraying and field monitoring costs. The "standard" strategies with fungicide treatments at fixed time intervals only have treatment costs, including chemicals, labor, fuel and other costs, whereas the "Mildium" strategy creates labor costs for field monitoring. These components of the partial gross margin are presented in Fig. 5b.

Fig. 5 shows that the main factors affecting the gross margin are yield reductions, because in our economic context, the costs are low relative to the gross product. The "14 days" strategy provides the highest mean gross product, which is sometimes reduced some years by low potential yields more than by yield losses. In the "Mildium" strategy, a large part of the yield loss that was caused by the pathogen was included in the non-marketable yield when applying the regulatory upper bound, resulting in an average gross product very close to that of "14 days". The average margin was lower than in "14 days" because the decrease in the spraying cost was lower than the added cost of field monitoring. The other systematic strategies showed a large decrease in the gross product because of the disease's effect on both yield and quality, which was not compensated by the cost reduction.

Fig. 6 shows the statistics of this partial margin and the number of treatments on the series of years for each strategy. The average values allow a general comparison, and the quartile and medians indicate the range of variation; the height of the quartile box can be considered as a visual index for the variability of the economic result.

When considering only "systematic" strategies, the variability between years increased and the average level of protection against loss of profit due to downy mildew decreased when the time interval between sprayings increased. The "Mildium" strategy performed slightly less well than the "14 days" strategy in terms of average margin (2.7% lower), whereas all other strategies resulted in significant margin losses (12.8%, 20% and 57.2% lower than "14

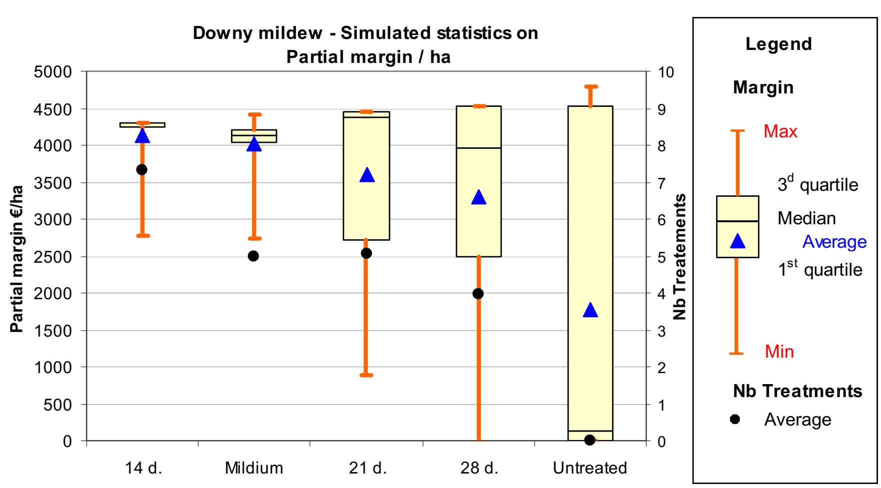

Fig. 6. Frequency analysis of five downy mildew control strategy impacts on the partial margin per ha from a vineyard plot in "La Ferrade" (near Bordeaux, France), based on the simulation of 23 annual weather patterns between 1988 and 2010.

days" for the "21 days", "28 days" and "no fungicide" strategies, respectively). Furthermore, the low variability of the "Mildium" strategy makes it as protective for the grower's income and the sustainability of the farm as the "14 days" strategy. The three other strategies showed much higher variability, and are therefore much more risky in terms of grower income.

4. Discussion and conclusion

The present work was intended to build a grapevine-downy mildew model in which the disease development, damage, yield loss and economic consequences could be quantified in a simple but realistic way in order to simulate, evaluate and compare fungicide treatment strategies and their effect on grower income. The aim was to offer a tool for assessing fungicide strategies, but this model should not be considered as an operational decision support tool. This paper explains the approach we chose and presents one example of an application. The parameter estimations and the evaluation of the control strategies showed the ability of our model to simulate downy mildew impact on a vineyard and to estimate the efficacy of a range of control strategies.

The simulator includes rather simple equations representing *P. viticola* development and its damage on grapevine plants relative to more specialized pathological models. For example, Rossi et al. (2009) proposed a more detailed model for primary infections (Caffi et al., 2009, 2011); Vercesi et al. (2010) suggested a modeling approach to *P. viticola* oospore germination dynamics that demonstrated showing the importance of both climatic and endogenous factors and Calonnec et al. (2008, 2009) precisely quantified host–pathogen relations in the case of grapevine powdery mildew. Sporulation and its decline over time can also be described in a more detailed manner than in our model; for example, Hill (1989) related the sporulation of individual lesions to the temperature over 2–3 months, and Kennelly et al. (2007a) found that spore production decline was more accurately related to the number of repeated cycles of sporulation. All developmental steps of *P. viticola* on the grapevine plant have been thoroughly studied, while data and models of this development have been proposed, providing useful insights into this field (Park et al., 1997; Kennelly et al., 2004, 2007b; Rossi et al., 2009). However, such detailed models cannot include all disease development stages, as well as damages and yield loss, to produce economic results. On the other hand, Orlandini et al. (2008) used an agrometeorological approach to more generally simulate the effect of downy mildew on grapevines, but their approach did not include yield reduction or economic consequences. In the 1990s, Rosa et al. (1993, 1995) produced a software package (PLASMO) that was aimed at simulating downy mildew development in the grapevine to better schedule fungicide treatments, but it did not include the resulting loss of yield or economic consequences related to treatment choices.

Although our model was constructed with simple assumptions, it was proven to represent the actual damage observed on leaves and grapes accurately enough to simulate economic results for a growing season with a given treatment strategy. Using more detailed models for each stage of disease development and damage might have provided more information on certain parts of the patho-system but would have required a huge model with numerous parameters and long parameterization times, which would not be suitable for our intended purpose.

The results of our parameter estimations showed that the model in its present form is able to represent some of the key elements of grape downy mildew development well enough to represent our field data, including the occurrence of primary and secondary infections. However, because the parameter estimates and model evaluations were conducted with data that were collected from untreated vineyards, the functions that account for fungicide protection were not evaluated through a comparison of simulated and measured data. Therefore, we chose a simple linear method to describe the decline of fungicide efficacy through time, which is coherent with previous published observations (see for example Latin, 2006). The proposed linear representation can easily be adapted to specific data on a given fungicide when available. Some other components of the model include parameters for which appropriate values are difficult to obtain, which could come from a lack of biological knowledge or experimental methods, as noted for example by Skelsey et al. (2009) in relation to dispersal of potato blight inoculum. In our model, this lack of knowledge could be relevant to PI_{area} for example. For this reason, we are implementing a tool that allows the user to change such parameters to a range of values and associated probability distribution instead of a fixed value. This will help accounting for a level of uncertainty that is associated with this parameter's value.

The main output of our model is the estimation of a partial margin for a given vineyard, depending on the annual weather pattern and the control strategy adopted by the grower. The variations in this margin may be linked to cost changes or to gross product variations. The different factors that influence the gross product include a year/weather effect on the potential yield, the disease effect, and regulatory effects such as maximal marketable yield or a reduced price if the crop is badly infected. If the potential yield for a specific year is above the maximal marketable yield, the yield loss caused by the disease may not modify the gross product. Therefore, the estimates of economic results, as opposed to the percentage of damage done, depend on the potential yield estimated by STICS. STICS was one of the very few crop models that could produce the necessary information for a disease model, but we know the absolute value of the potential yield is sometimes overestimated, depending on the weather pattern. However, for relative purposes such as crop protection strategy comparisons, STICS produced acceptable values. Furthermore, the modular structure of the simulator would allow the use of an alternative model for grapevine simulation very easily, if available.

Among the factors that may alter the estimated cost, some are part of the economic context and were not included in the model except as simple parameters; the fungicide cost for example may undergo commercial or regulatory variations through such adjustments as changes to tax rates. Other variables were included in this study, such as the number of sprays and field observations. The cost of field observations may vary, not only due to the labor cost, but also because the sampling that is conducted on a given plot may be used to represent this plot alone or mat represent several nearby plots of the same variety that are grown in similar conditions. This ability to extrapolate the treatment decisions to nearby vineyards may thus affect the cost per hectare of field observations. Additionally, the actual treatment frequency is also influenced by other factors, such as availability of manpower, changes in current weather, etc. The strategies under examination should therefore be considered as schematic models, and other elements that modify the actual treatment decisions could be implemented in the model as long as we can synthesize them as decision rules.

The results in this paper include parameter estimation and an illustration of the possible use of the model in evaluating pesticide treatment strategies. Among the tested protection strategies, we found that overall, the "Mildium" strategy appeared to be more protective against losses from downy mildew than the "21 days" strategy with a lower variability. But "Mildium" appeared less protective than the "14 days" strategy, which is the closest to current practices in French vine-growing regions. The "Mildium" strategy is based upon a decision tool that requires a good knowledge of the pathological context as well as field surveys that are performed during the season to adjust treatment decisions; this result supports the view that reducing pesticide use while preserving economic results is not a trivial question and requires a fine analysis of both the general context and local conditions. Furthermore, adopting an adaptive protection strategy, such as "Mildium", allows to significantly reduce the use of fungicide (from 7.3 to 5 treatments in average when changing from "14 days" to "Mildium"), which answers a social demand. However, the adaptive protection strategy also has "costs" other than economic ones, such as the need for more flexibility in fungicide application and grower organization and the need for trained observers for field monitoring. Winegrowers may not all be ready to accept these changes.

The validity of this model is not known outside the conditions in which we estimated and tested it, i.e., in Merlot vineyards of the Bordeaux region under climatic conditions corresponding to those encountered during the past 20 years. The model is presently undergoing validation tests on other years and climatic conditions in Merlot vineyards within the Bordeaux region with the objective of extending its field of application. The first of these extensions is the study of powdery mildew, which is caused by *Erysiphe necator*. This is important because both field monitoring and spraying can be conducted simultaneously for both diseases and the costs should therefore be estimated as a whole. Different fungicides or other control strategies or crop management, such as organic practices, may also be evaluated with this tool (Dagostin et al., 2011).

However, to expand the field of application of this tool, the model will need to be usable in other regions outside the Bordeaux area. For that reason, we need to test it on other grapevine varieties, which will require different parameter values, and most likely different sensitivities to fungal diseases. The fungal strains that are encountered in other wine-growing regions may also have different climatic determinants, leading to different disease dynamics. Finally, the economic context of grapes and wine production is highly region-dependent; the price and maximal yield that are fixed by the registered designation of origin will vary considerably according to the given location.

Because this model was built as a tool for pesticide strategy evaluation, it can be used as an aid in advising policy makers about pesticide use regulation. To promote pesticide reduction, the model can help to estimate, for example, the effects of policies, such as tax changes on chemicals or increased prices for low-pesticide grapes and wine, on the income of growers adopting different strategies.

Alternatively, because the yearly weather is explicitly taken into account, the model could be used to estimate the possible evolution of grapevine grower's income in response to protection costs and in the context of climate change (Francesca et al., 2006).

Acknowledgments

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Appendix. List of variables, parameters and functions used and their units

A1
Variable list.

Symbol	Meaning	Unit
t	Day of simulation	integer
d	Day of last spraying	integer
flowering	Flowering day	integer
harvest	Harvesting day	integer
st	Protection strategy	integer
y	Climatic year	integer
$LA_T(t)$	Total grapevine leaf area at time t	ha of leaf area per ha of vineyard
$LA_I(t)$	Infected leaf area at time t	Same as $LA_T(t)$
$LA_R(t)$	Ontogenic resistant leaf area at time t	Same as $LA_T(t)$
$LA_P(t,d)$	Fungicide-protected leaf area at time t	Same as $LA_T(t)$
$LA_S(t)$	Healthy susceptible leaf area at time t	Same as $LA_T(t)$
$LA_{spor}(t)$	Sporulating leaf area at time t	Same as $LA_T(t)$
$\Delta LA_I^P(t)$	Increase in infected leaf area due to primary infection at time t	Same as $LA_T(t)$
$\Delta LA_I^S(t)$	Increase in infected leaf area due to secondary infection at time t	Same as $LA_T(t)$
$Stage(t)$	Stage of phenological development at time t	integer
$Rain(t)$	Rainfall amount on day t	mm
$Tmean(t)$	Average temperature on day t	°C
$PI_{nb}(t)$	Cumulative number of primary infections at time t	integer $\in [0;PI_{maxnb}]$
$Sever_L(t)$	Severity of downy mildew infection on leaves (% of infected leaves)	$\in [0;1]$
$Sever_Y(t)$	Severity of downy mildew infection on reproductive organs (% of infected berries)	$\in [0;1]$
$g_{pot}(t)$	Potential pre-flowering fraction of grapes and berries at time t	Normalized, $\in [0;1]$
$g_{loss}(t)$	Loss of grapes and berries due to pre-flowering infection by *P. viticola*	$\in [0;1]$
$g(t)$	Actual fraction of young grapes and berries before flowering, at time t	$\in [0;1]$
G	Fraction of young grapes and berries at flowering	$\in [0;1]$
$y_{pot}(t)$	Potential yield at time t	t/ha
$y_{loss}(t)$	Loss of yield due to berry infections by *P. viticola* at time t	t/ha
$y(t)$	Simulated yield at time t	
$Y(st, y)$	Simulated harvested yield of year *y*, taking into account loss caused by downy mildew when applying strategy *st*	t/ha
$Y_{mark}(st,y)$	Marketable yield in year *y* when protection strategy *st* is applied	t/ha
$P(st,y)$	Sale price of grapes in year *y* when protection strategy *st* is applied	€/t
$GP(st,y)$	Gross product in year *y* when protection strategy *st* is applied	€/ha
$NbS(st,y)$	Number of fungicide sprayings in year *y* with protection strategy *st*	integer
$NbO(st,y)$	Number of field observations in year *y* when applying protection strategy *st*	integer
$C(st, y)$	Total cost of sprays and observations on year *y* with protection strategy *st*	€/ha
$M(st, y)$	Partial gross margin in year *y* with protection strategy *st*	€/ha

A2
List of the parameters and functions.

Symbol	Meaning	Unit
PI_{begin}	Beginning of the period of susceptibility to primary infections	date
PI_{end}	End of the period of susceptibility to primary infections	date
$PI_{minrain}$	Minimal amount of daily rain necessary for primary infections	mm
$PI_{mintemp}$	Daily temperature threshold for primary infections	°C

(*continued on next page*)

A2 (*continued*)

Symbol	Meaning	Unit
PI_{maxnbn}	Maximal number of primary infections possible	integer
PI_{area}	Newly infected leaf area per day when primary infection is possible	ha of leaf area per ha of vineyard
$SI_{minrain}$	Minimal amount of daily rain necessary for secondary infection	mm
$SI_{mintemp}$	Daily temperature threshold for secondary infection	°C
latency	Duration of latency period (calculate with T°)	Number of days
sporul	Duration of spore production on an infected leaf	Number of days
sp_{triang}	Shape parameter of the sporulation function	No unit; ∊ [0;1]
resist	Age at which leaves begin to acquire ontogenic resistance	Number of days
K_L	Infective potential of sporulating surface at every occurrence of secondary infection on leaves	No unit
K_{early}	Infective potential of sporulating surfaces towards reproductive organs before flowering	No unit
K_{Late}	Infective potential of sporulating surfaces towards reproductive organs after flowering	No unit
$chem_{effic}$	Ratio of infection reduction by fungicide	No unit; ∊ [0;1]
$chem_{life1}$	Number of days of total efficacy for a fungicide spray	integer
$chem_{life2}$	Number of days of efficacy decrease from 1 to 0 for a fungicide spray	integer
$Prot_{early}(t,d))$	Efficacy of protection by fungicide of reproductive organs before flowering at time t. Same parameters as for the foliar protection	∊ [0;1]
$Prot_{late}(t,d)$	Efficacy of protection by fungicide of reproductive organs after flowering at time t. Same parameters as for the foliar protection	∊ [0;1]
$Susc_{early}(t)$	Susceptibility to infection of reproductive organs before flowering	∊ [0;1]
$Susc_{late}(t)$	Susceptibility to infection of reproductive organs after flowering	∊ [0;1]
Y_{max}	Maximal marketable yield for one hectare in the protected designation of origin	t/ha
p	Basic sale price of yield	€/t
R_D	Rate of disease that lead to a sale price decrease	ratio
R_P	Rate of reduction in sale price	ratio
C_S	Cost of one fungicide spraying	€/ha
C_O	Cost of one field observation on downy mildew infection level	€/ha

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