Research Article

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Field evaluation of an expertise-based formal decision system for fungicide management of grapevine downy and powdery mildews

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Abstract

BACKGROUND: In France, viticulture accounts for 20% of the phytochemicals sprayed in agriculture, and 80% of grapevine pesticides target powdery and downy mildews. European policies promote pesticide use reduction, and new methods for low-input disease management are needed for viticulture. Here, we present the assessment, in France, of Mildium®, a new decision support system for the management of grapevine mildews.

RESULTS: A 4 year assessment trial of Mildium has been conducted in a network of 83 plots distributed across the French vineyards. In most vineyards, Mildium has proved to be successful at protecting the crop while reducing by 30–50% the number of treatments required when compared with grower practices.

CONCLUSION: The design of Mildium results from the formalisation of a common management of both powdery and downy mildews and eventually leads to a significant fungicide reduction at the plot scale. It could encourage stakeholders to design customised farm-scale and low-chemical-input decision support methods.

Supporting information may be found in the online version of this article.

Keywords: disease management; decision support system; *Vitis vinifera*; crop protection; decision process

1 INTRODUCTION

Downy mildew (*Plasmopara viticola*) and powdery mildew (*Erysyphe necator*) concern vinegrowers worldwide. These two diseases can lead to severe injuries and result in significant commercial losses. Leaf injuries and defoliation caused by downy mildew can affect photosynthetic rate and grape maturation.[1,2] The qualitative damages caused by powdery mildew on bunches lead to organoleptic defects in wines and off-flavours as well.[3,4] On *Vitis vinifera* cultivars used for vine production, crop protection against downy and powdery mildews rests mainly on the use of fungicides with repeated preventive applications during the vegetative period. In France, the mean treatment frequency index (TFI) (the index used to monitor the intensity of protection by chemicals) for the control of vine pathogens and pests was respectively 12.2 and 12.5 in 2006 and 2010.[5,6] On average, 90% of the TFI value results from applications that target powdery and downy mildews. It is also important to acknowledge the high variability in protection practices, even within an area that encounters a homogeneous bioclimatic risk. Depending on the grower tolerance to downy and powdery mildews, the risk aversion factor is often mentioned to explain this variability. Production constraints and work organisations also affect the crop protection strategy and plant protection tactics.[7]

In the last decade, in Europe, several countries have developed action plans to reduce the use of pesticides and the risks linked to this usage.[8] In France, the Ecophyto 2018 plan[9] was set up in 2008. Its objective was to reduce by half, 'if possible', and before 2018, the use of pesticide, according to the TFI indicator. The need for innovative crop protection strategies and enhanced day-to-day tactics is an ever-growing concern for the research community.

Several decision support systems (DSSs) are available to growers, consultants and extension services. Yet most of these DSSs consist of epidemic development risk models and are based on climatic data. These models provide both current and forecast risk levels by integrating past climatic data and weather forecasts.[10–13] The recent development of web platforms, such as Agrometeo.ch, Vitimeteo.de, vignevin-epicure.com and ViteBio.net, has facilitated the transfer of information from risk model providers to growers and advisors. Yet the interpretation of risk data for deciding and

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scheduling phytosanitary applications is generally not mechanistic. However, some authors have proposed decision support rules based on warning systems for powdery mildew with thresholds that are set according to empirical weather-driven models. For instance, the degree-day model,[14] the grape powdery mildew risk assessment index[15] and the OiDiag system[16] were developed for the purpose of deciding when to start application and adapting the maximum time lag from one application session to the next. Caffi *et al.* have also proposed a rule-and-threshold-based DSS for managing powdery mildew that relies on the outputs of a mechanistic pathosystem model.[17] Coptimizer is another model-driven DSS[18] designed to optimise the rate of copper-based fungicide use in organic viticulture against grapevine downy mildew.

However, these DSSs do not allow the management of both downy and powdery mildews in the same process. Yet it is well known that growers often save working time by mixing products in their spraying tank. We hypothesise that combined decision support for both mildews may fit operational needs of growers and advisers. We formulate here a few remarks about the decision-making chain, from risk assessment to scheduling of sprayings, that support this hypothesis. First of all, risk associated with powdery and downy mildews may evolve over a period as short as a few days or following a few millimetres of rainfall. Theoretically speaking, risk should therefore be monitored at the same time as spraying resources are planned. Yet we can assume that many growers do not revise their application plans as often as risk evolution would suggest. A second observation is that, although the dynamics of disease propagation may be fast, an assessment of risk at the plot is not made each time a decision needs to be taken or revised. There are at least two reasons for this. The first reason is that it would be cost prohibitive to perform accurate field assessments each time a decision is needed. The second reason is that the time lag from infection to symptoms and the difficulty to detect early symptoms[19] can make it difficult to rely only on field assessment for the prediction of disease evolution. From these observations, we hypothesise further that a DSS that would combine management of both downy and powdery mildews on grapevine should not only be based on reactive treatments. We call reactive treatment the method that combines frequent assessment of disease level in a plot and the organisation of a treatment as soon as a predefined threshold has been exceeded.

Considering that combined management of both mildew diseases seemed relevant and that there was no report of such a combined DSS in the literature, an experiment was set up in order to design a novel decision support system based on a new organisation of information-gathering and decision-making over time. We decided that the novel design should be checked against field experiment results obtained on many plots. In order to ensure that the decision system that would be applied to many plots by many experimenters had consistent logics and appropriate time behaviour, we made a model of it.[20] The primary goal of our decision system is to reduce the number of treatments while providing growers with crop protection that meets their needs regarding plot yield and bunch quality.

To summarise, research objectives included the design of a theoretical prototype decision support system, called Mildium® in France, the design of a protocol for testing the decision system on many plots in many climatic conditions and the evaluation of the performance of the prototype in different production areas over several years. Mildium is a contraction of the French names for the two diseases.

2 MATERIALS AND METHODS

2.1 Principles and overview of the tested prototype decision support system

The following requirements were proposed for the decision system: (i) combination of bioclimatic information and plot assessment results; (ii) synchronisation of treatments against both mildews in a single application when protection against both powdery and downy mildew is needed; (iii) provision of reasonably fast and accurate sampling methods for plot assessments; (iv) limitation of the number of assessments needed. Please note that in previous publications about its modelling, Mildium has been called GrapeMilDeWS, which stands for Grape Mildews Decision Workflow System. The formal model of GrapeMilDeWS has been thoroughly described by Léger *et al.*[20,21] Léger and Naud[22] developed the method used to build this model on the basis of interviews with the pathologists who defined its principles and drafted its logics. The present paper is about field evaluation of the decision system.

2.1.1 Important facts about the pathosystems

Grapevine powdery mildew and downy mildew pathosystems have been extensively studied by different research groups. We recall here some important facts about these pathosystems that were considered during the design of the Mildium decision system.

Powdery mildew epidemics are triggered by two potential sources of primary infection: ascospores released from cleistothecia that overwinter in the bark of the vine[23] and new shoots colonised by remaining mycelium that overwinter within dormant buds.[24] Sporulating lesions, which infect new susceptible leaves, result in secondary infections, and the colonised leaves represent a source of infection for developing berries. A direct relationship has been established between the early development of the disease in leaves and subsequent injury to grapes.[25,26]

Downy mildew epidemics are initiated by zoospores released from oospores that overwinter in the soil. Lesions from these primary infections produce sporangia, containing asexual zoospores, that can lead to secondary infections. Primary and secondary infections require water. Therefore, the disease spreads mostly during rainy events. It has been shown that oosporic infections can occur any time in the season.[27,28] Thus, there are strong grounds for the hypothesis that downy mildew epidemics are driven by both oosporic and secondary infections.[29,30]

One fact that is common to both diseases is that cluster susceptibility is maximal at the flowering stage and fruit set, and decreases until bunch closure. The susceptibility period is shorter for powdery mildew[31,32] than for downy mildew.[33]

Based on this knowledge, the decision system prototype was built on the basis of several assumptions: (i) there is a link between precocity and severity of epidemics, and thus early monitoring of epidemics, especially for powdery mildew, should help to determine the potential risk level and to manage treatments; (ii) the flowering period needs to be protected to ensure a good and robust efficacy of the strategy; (iii) downy mildew treatments should be mostly applied before rainy events, so as to prevent further spreading of the disease.

2.1.2 Design and structure of the Mildium prototype decision system

It is based on a sequence of decision stages, where each stage should include, at most, one application against each disease

Table 1. Description of the different steps of the Mildium prototype: implementation period, treatment and indicators used

			Treatment			
Stage	Beginning[a]	End[a]	No.	Downy mildew	Powdery mildew	Indicators used[b]
0	09	FA1 (15–17)	T0	Optional	–	ILM, PA
1	FA1	FA2 (18–20)	T1	Optional	Required	FA1, ILM, PA
2	FA2	60	T2	Optional	Optional	FA2, ILM, PA
3	61	69	T3	Required	Required	-
4	15 days after T3	FA3 (77–79)	T4	Optional	Optional	FA1 (PM/DM), FA2 (DM), ILM, PA
5	FA3	81	T5	Optional	Optional	FA3, PA
6	81		T6	Required	–	–

[a] Beginning and end of the stages should be a field assessment (FA) or a phenological stage according to the BBCH scale:[46] 09 – bud burst; 60 – first flowerhoods detached from the receptacle, 61 – beginning of flowering–10% of flowerhoods fallen; 69 – end of flowering; 81 – beginning of ripening.

[b] Indicators used: ILM – downy mildew risk at the local scale; FA – field assessment; PA – rain forecast.

(Table 1). For some stages, treatments are deemed to be obligatory in the protocol, and only their time position within the stage time period can be modified according to available information. These obligatory treatments are denoted as 'required'. The designers of the decision system considered that it was required for safe protection that an application against powdery mildew be applied well before flowering. Therefore, the decision protocol specifies that a powdery mildew treatment should be performed during stage 1 if some powdery mildew has been observed, and at the latest 1 week after the end of stage 2 even if no powdery mildew has been observed. At flowering, spraying against both powdery and downy mildew is considered to be 'required'. The last obligatory treatment is scheduled at mid-veraison, and is copper based. This treatment is for maintaining reasonably healthy foliage, as far as downy mildew is concerned, during maturation of grapes. The other potential applications that are defined in the decision protocol are denoted as 'optional': for each optional treatment, the decision to apply it is made according to a set of indicators that are related to the potential further development of epidemics.

There are two categories of indicators used in Mildium: the ones based on information collected at the plot, and the ones based on information collected about the current bioclimatic situation within the production area. Observations of symptoms, for both diseases, fall into the plot information category. The Mildium observation protocol includes explicit data interpretation in order to convert quantified symptom levels, at the plot scale, into qualitative risk classes. For operational purposes, the number of field assessments conducted to provide information for the decision system on disease symptoms has been limited to three per growing season. Two field assessments are conducted between bud-break and flowering. The first (FA1) is to be scheduled between BBCH stages 15 and 17. The second (FA2) is to be scheduled between BBCH stages 18 and 20, i.e. approximately 2 weeks after FA1. These assessments are meant to identify early epidemics. The third and final field assessment (FA3) is to be scheduled approximately 4 weeks after the treatment performed at flowering (T3). It should be done before BBCH stage 77 (bunch closure).

Quantitative data from field assessments are encoded, based on thresholds, in qualitative variables. Each takes on two or three discrete values with the following meaning: the '–' symbol stands for 'moderate to null incidence of the disease'; the '+' symbol corresponds to an incidence scale from moderate to strong; the '++' symbol identifies very strong incidence. The thresholds are disease specific and depend on the crop growth stages, so as to take into account the evolution of the actual risk of injuries and potential yield loss (Table 2).

As far as downy mildew is concerned, Mildium involves two other indicators, on a wider spatial scale. The ILM indicator is to be evaluated by users of the Mildium DSS according to information on risk at the local scale and their expertise. This information includes results of bioclimatic models and information from the routine plot assessments provided by extension services. The decision protocol provides interpretation guidelines to assess ILM. ILM has two qualitative values: it is either set to '–' (null or low risk) or to '+' (medium to high risk). When short-term prediction of rainfall quantities is available, these need to be taken into account when assessing ILM. The second indicator at the local scale is about forecast of rain events. Each forecast rain event is evaluated with regard to its potential to contribute to the propagation of the epidemics. If it is not considered potentially harmful, the indicator (PA) is set to '–'. In the opposite case, PA is set to '+' and the soonest such event is the one considered in the decision.

There are seven decision stages in the prototype decision system (see table 'stages'). The first one starts at bud-break. The last one ends at mid-veraison. The change from one decision stage to another can be triggered by a phenological event, the report of a field assessment (FA) or the end of a delay expressed in the number of days since a preceding treatment. Within one decision stage, at most one treatment against each disease can be decided. The decision about the utility and scheduling of each treatment is made according to the different indicators explained before, and is based on precise timings and logics. The prototype decision system schedules a minimum of four treatments that are defined as required (see above and table 'stages') and a maximum of eight optional treatments. Consistent with grower practices, when treatments against both diseases are decided and can be scheduled at the same time, they are combined in a single application. This avoids unnecessary costs such as scheduling one application closely after another. The T3 stage consists of such a combined application targeting both diseases.

2.2 Contents of the decision protocol

The decision system has been modelled in Statecharts language.[20,22] This notably enabled us to evaluate the consistency of its logics and timings. For practical reasons, because running the Statecharts model would have required the setting

Table 2. Assessment methodology and the thresholds used for the implementation of the prototype in the experimental network

Field assessment	Powdery mildew Threshold[a]		Powdery mildew Assessment methodology	Downy mildew Threshold[a]		Downy mildew Assessment methodology
FA1	0−	0–2%	Eight leaves per plant (levels 1 to 3 from the bottom of the shoot)	M−	0%	Whole plant
	0+	2–10%		M+	1–10%	
	0++	>10%		M++	>10%	
FA2	0−	0–20%	Eight leaves per plant (levels 4 to 6 from the bottom of the shoot)	M−	<10%	Whole plant
	0+	>20%		M+	10–50%	
				M++	>50%	
FA3	0−	0–20%	Five bunches per plants (in the middle part of the vine)	M−	<10% or FA3-FA2 ≤ 0	Whole plant
	0+	>20%		M+	10–50% and FA3-FA2 > 0	
				M++	>50% and FA3-FA2 0	

[a] Disease incidence on plants except for FA3/powdery mildew disease incidence on bunches.

of a complex computing environment for each user, the model was translated into a set of printed decision trees. It was distributed to each person in charge of experimenting with Mildium in its printed form. These people were mostly technicians from extension services. A short training on the Mildium decision trees and experiment protocol was provided when requested. There is one decision tree per decision stage. An example of the printed decision tree for stage 4 is given in Fig. 1. The complete set of decision trees is provided in the supporting information.

Besides decision trees for each stage, the protocol also included a description of indicators and sampling methods, and a crop protection assessment protocol.

2.3 Field experiments

From 2008 to 2011, the Mildium prototype was implemented on a network of plots scattered over French vineyards representing a variety of cultivars and agroclimatic conditions. Three wine-growing areas can be distinguished: Atlantic, northern and southern.

The combination of rainfall water quantities and temperature during the vegetative phase is different in each of these areas. Average data prepared from a 20 year history are given in the supporting information (Table S1).

The Atlantic and northern areas are characterised by a high risk of downy mildew epidemics, and a variable risk of powdery mildew. The southern area is characterised by a generally low risk of downy mildew and a high risk of powdery mildew.

The number of experimental sites and their location are detailed in Fig. 2 and in supporting information Table S2.

Each plot was divided into two blocks: Mildium and reference. The Mildium block was treated according to the Mildium prototype; the reference block was sprayed according to the grower's criteria (timing of application, fungicides, application rate). No untreated plot or plot part is included in the setting, so as avoid interactions with the treated plots which may have perturbed the comparison between the Mildium and reference blocks.

Each block in the plot included at least 1000 plants, regardless of plant density. For the Mildium block of each plot, experimenters assessed the values for the indicators, and made decisions according to the protocol. Fungicide treatments were performed by growers using their usual sprayer.

These indicator value assessments were performed on an evenly distributed sample of 10% of the plants (one plant every ten plants, then at least 100 plants per block are sampled). The sampling methods for leaves and clusters were specified for powdery mildew. As for downy mildew, a global assessment of the whole plant was used to classify plants as infected or not (a plant is classified as infected as soon as one symptom is detected on any leaf). The assessment methodology and the thresholds used for the implementation of the prototype are presented in Table 2.

The assessment of prototype performance was based on the following criteria: disease severity on leaves and clusters, amount of fungicide used and grower satisfaction with regard to their production targets.

For each block, an evenly distributed sampling of 3% of all plants was used to assess downy and powdery mildew severity (then, at least 30 plants were sampled for each block). The assessments were performed at the 'veraison' stage for bunches and just before harvest for leaves. Disease severity for bunches was assessed as the percentage of tissue area covered by lesions for each cluster. The severity on leaves was assessed as the percentage of symptomatic tissues with respect to whole foliage of each vinestock.

For each disease, the amount of fungicide used is expressed by the TFI, which is calculated as follows:

$$\mathrm{TFI} = \sum_{\text{treatment}} \frac{(\text{applied rate})\ T}{(\text{registered rate})\ T}$$

A satisfaction survey was conducted among growers to analyse whether the Mildium and their own reference strategies had met their expectations, which may vary with the region, the type of production and their perceptions. The questionnaire was divided into three sections corresponding to the following criteria: visual assessment of disease symptoms, yield and grape quality. For each experimental plot and each block (with respective Mildium and reference strategies), the following scoring method was proposed: satisfactory results (score 1) or unsatisfactory results (score 0). This produced four outcomes for each plot*year combination. When both strategies gave satisfaction (score 1), the case was considered as a true positive case (TP). The case was a false positive (FP) when score 1 was obtained with the Mildium strategy and not obtained with the reference strategy. The case was a false negative (FN) when the Mildium strategy scored 0 and the reference strategy scored 1. The fourth case was true negative. A contingency table was derived for each of the three satisfaction criteria.

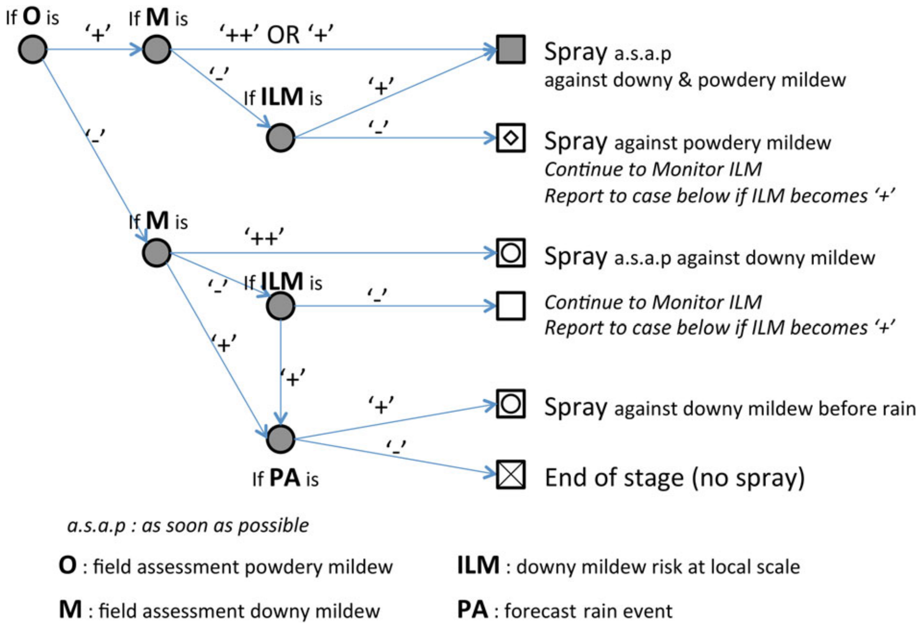
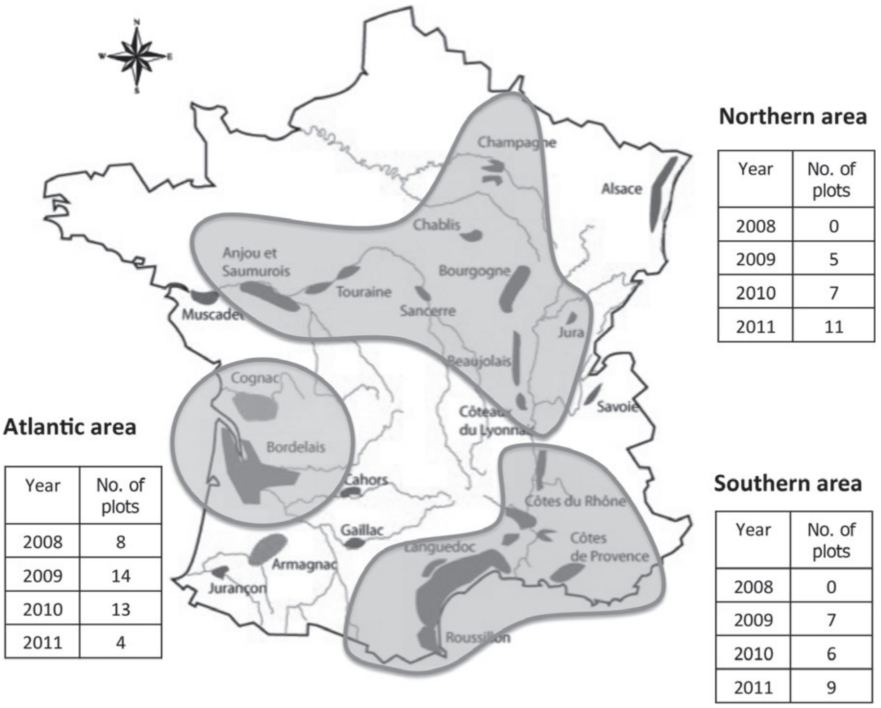


Figure 1. Illustration of the decision tree for stage 4 of the Mildium prototype.



Northern area

Year	No. of plots
2008	0
2009	5
2010	7
2011	11

Atlantic area

Year	No. of plots
2008	8
2009	14
2010	13
2011	4

Southern area

Year	No. of plots
2008	0
2009	7
2010	6
2011	9

Figure 2. Annual and geographical distribution of the different plots used in this study.

2.4 Statistical analysis

Statistical analysis was performed using JMP Pro 9.0.2 software (SAS Institute, Chicago, IL) and R (R Foundation for Statistical Computing, Vienna, Austria: http://www.R-project.org/). The difference between the reference block and the Mildium block was tested for the following variables: disease incidence on bunches, disease severity on bunches, disease severity on leaves. The effect of the crop protection method (Mildium versus reference) was evaluated with a Wilcoxon signed rank test for paired samples. For analysis of the results of the satisfaction survey, the rate of true positive (TPR) was calculated as the ratio of TP to the sum of TP and FN for each of the three criteria. The McNemar chi-square test was computed with Yate's correction (the null hypothesis being that there was no difference between the two strategies).

3 RESULTS

3.1 Bioclimatic context

The disease levels observed over each of the 4 years of experiments were quite different. The year 2008 can be characterised by strong epidemics of downy mildew, especially in the Atlantic area. The epidemics set up early in the season and the injury to bunches

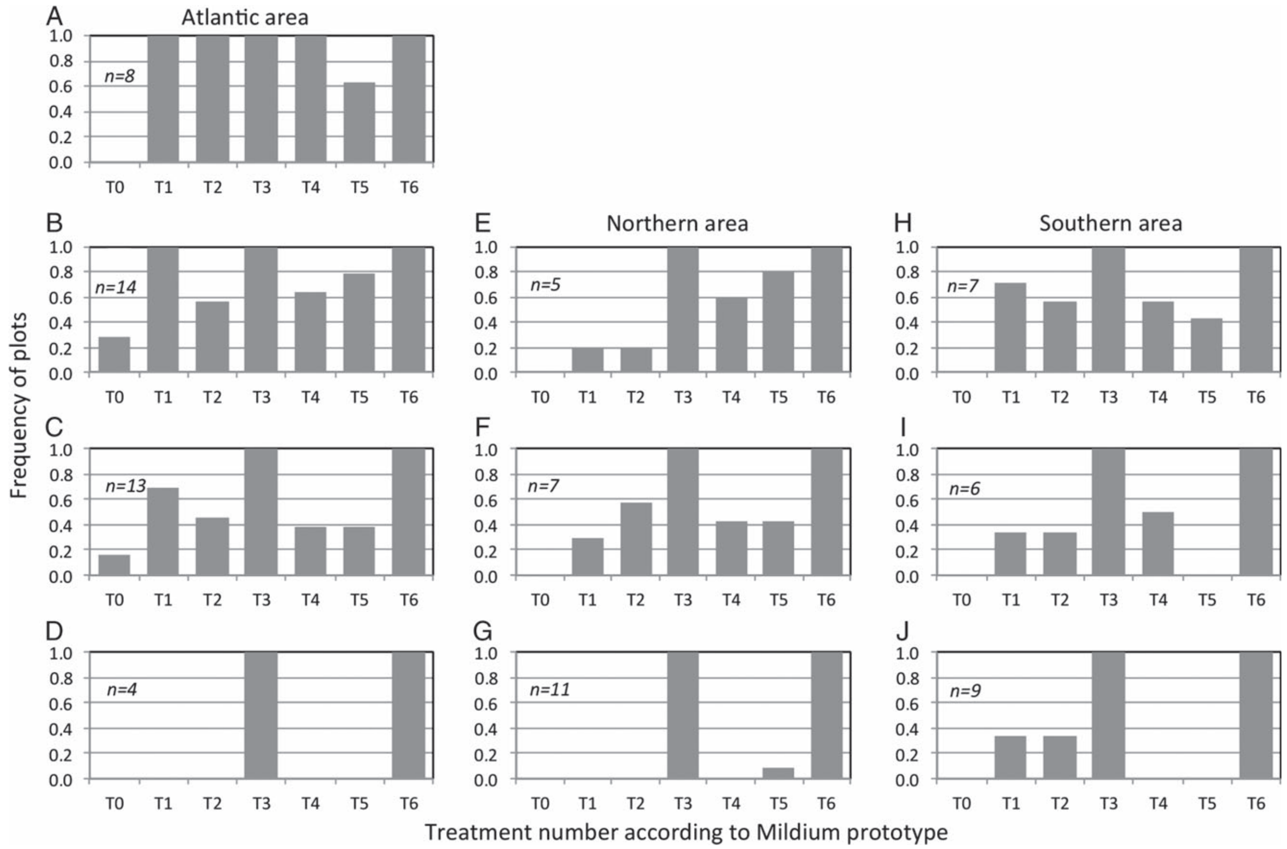


Figure 3. Frequency of sites at which the treatment T*i* for downy mildew management has been applied, where *i* is the index of the decision stage in the Mildium prototype. The first row (bar charts A, B, C, D) corresponds to the Atlantic area, the second (E, F, G) to the northen area and the third (H, I, J) to the southern area. The lines starting respectively with A, B, C and D bar charts correspond to the years 2008, 2009, 2010 and 2011; *n* is the number of sites for the year and the area.

were significant. Conversely, that year, the powdery mildew epidemics were rather weak.[34] In 2009, the downy mildew epidemic was weaker and less widespread than in 2008; however, there were some seriously affected areas (Grosman J, private communication, 2009). In 2010, the development of downy mildew was rather insignificant during springtime, except in the northern area, where local conditions sometimes led to bunch injury.[35] The epidemic pressure of powdery mildew was weak in the Atlantic area and more significant in the southern area. In the northern area, late development of powdery mildew was reported.

In 2011, downy mildew was absent until the beginning of veraison in the Atlantic and northern areas. After veraison, the epidemics propagated on leaves, sometimes resulting in severe foliar injury. In the southern area, the intensity of downy mildew epidemics was the norm, and much more severe than in 2010. The intensity of powdery mildew epidemics was, on average, standard, and rather more significant in the Atlantic area.[36]

3.2 Response of the DSS

Figures 3 and 4 show that the number of treatments performed on the basis of the Mildium decision system varied significantly according to years and areas. In some cases (Fig. 3, histogram D; Fig. 4, histograms A, B, C, D, E, G), only required treatments were applied. In other cases, most optional treatments were applied (Fig. 3, histogram A).

Figure 3 (histograms A, B, C) suggests that protection against downy mildew needs to be implemented earlier in the Atlantic area, and a few T0 treatments were applied. Figure 4 suggests that more treatments against powdery mildew are needed in the southern area, especially during the post-flowering period (T4/T5). In the northern area, the required treatment before flowering against powdery mildew was often applied during stage 2. The decision support system was designed to allow for synchronisation between downy and powdery mildew treatments when possible. Therefore, the later treatments against powdery mildew in the northern area are a consequence of the fact that treatments against downy mildew were performed later in this area than in the Atlantic area.

3.3 Technical performance

As can be seen in Fig. 5A, the average TFI for downy mildew on the reference plots decreases each year from 2008 to 2011 (from 6.9 to 3.5), which is consistent with the overall characteristics of the epidemics. Every year, the mean reduction in the TFI between the Mildium and reference plots is about 30%.

On reference plots, the average TFI for powdery mildew is approximately 4.5 (Fig. 5B) and is rather stable over the 4 years of experiment. The TFI indicator is clearly better for Mildium than for reference, with a 40% reduction in 2008 and an average 50% reduction for the years 2009 to 2011.

Figures 6A and B analyse crop protection performance with regard to bunches. As regards downy mildew, significantly lower performance was obtained over the two years 2009 (mean spread 9.6%) and 2010 (mean spread 3.9%, very small incidence level).

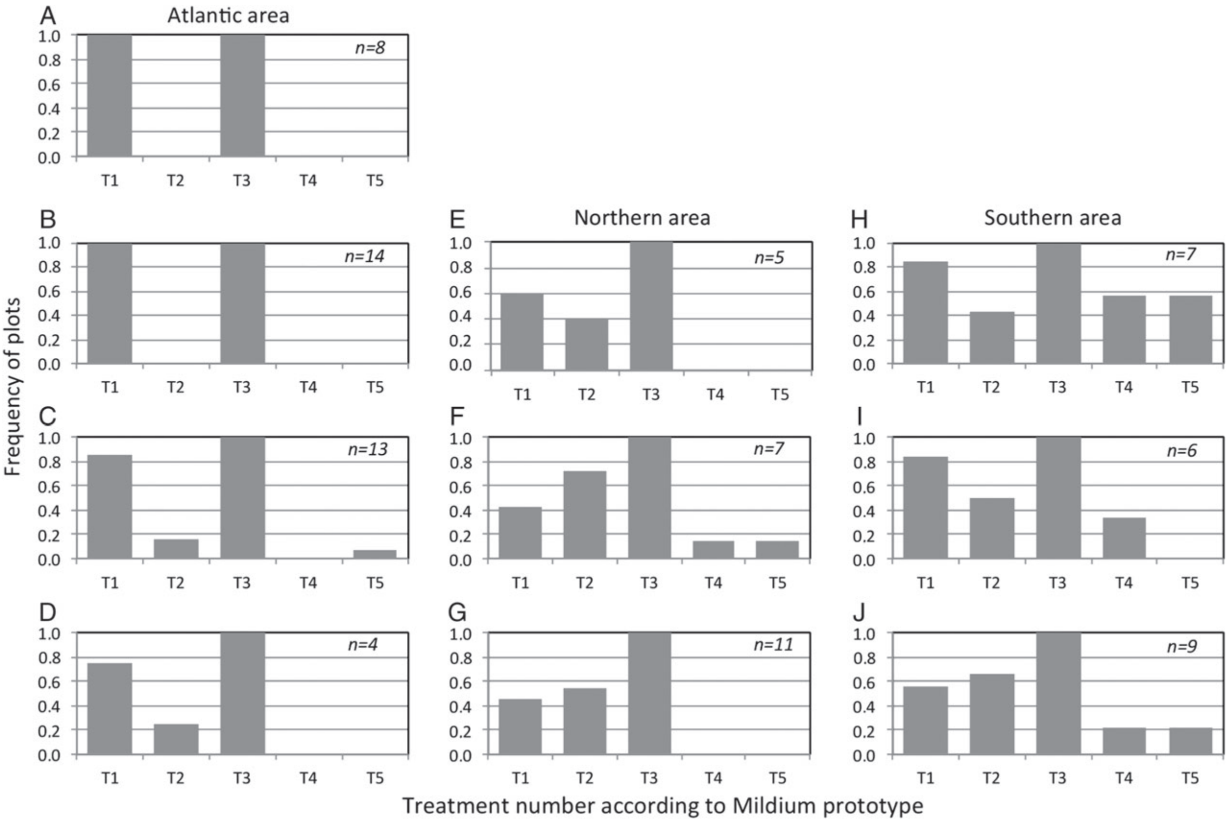


Figure 4. Frequency of sites at which the treatment T*i* for powdery mildew management has been applied, where *i* is the index for the decision stage in the Mildium prototype. The first row (bar charts A, B, C, D) correspond to the Atlantic area, the second (E, F, G) to the northen area and the third (H, I, J) to the southern area. The rows starting respectively with A, B, C and D bar charts correspond to the years 2008, 2009, 2010 and 2011; *n* is the number of sites for the year and the area.

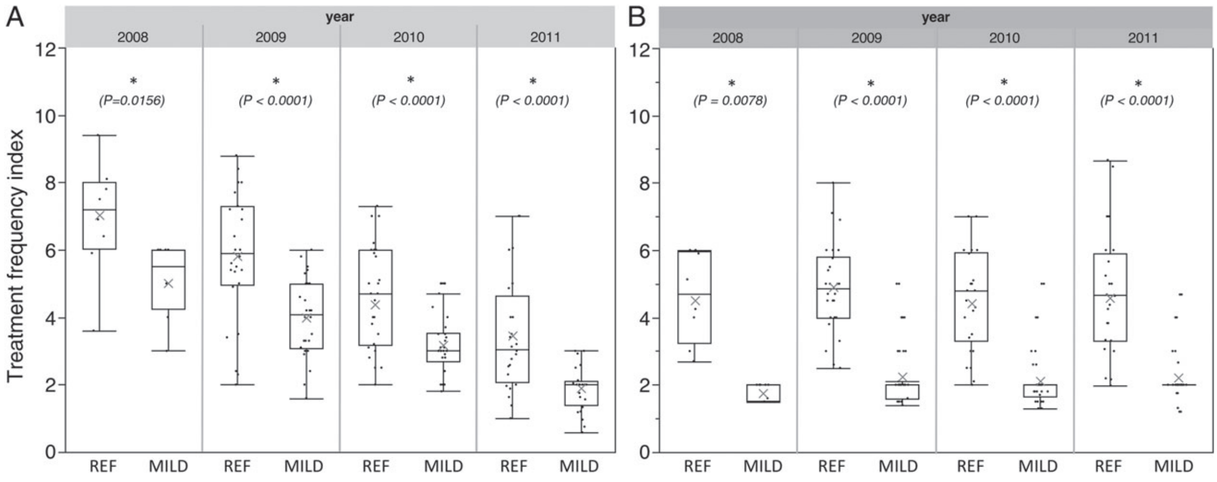


Figure 5. TFI distribution, for reference plots, of downy mildew (A) and powdery mildew (B) for the years 2008 to 2011, and comparison between Mildium (MILD) and reference (REF) blocks for each year. Combined box-and-whiskers plot and raw data. × denotes mean value of the data. The first and second whiskers are set to first quartile – 1.5*interquartile range and third quartile + 1.5*interquartile range respectively. No ns mark – the difference between Mildium and reference is always significant.

No statistical difference in crop protection can be established for the years 2008 and 2011. As for powdery mildew, three of the four years do not provide statistically different performance levels. In 2010, Mildium was less effective than reference, but the mean spread is small (1%).

Figures 6C and D complement Figs 6A and B with comparison of disease severity on bunches. As regards downy mildew, mean severities on bunches for Mildium blocks were 10, 2.5, 1.8 and 0.2% for the years 2008 to 2011 respectively. On reference blocks, severities were always below 3%. High crop protection performance was observed for the years 2009 and 2010, with respective mean spreads of 0.3 and 1.16%. In 2009, the mean spread was small, but it should be noted that the two reference blocks were rather poorly protected. As for powdery mildew, a significant difference

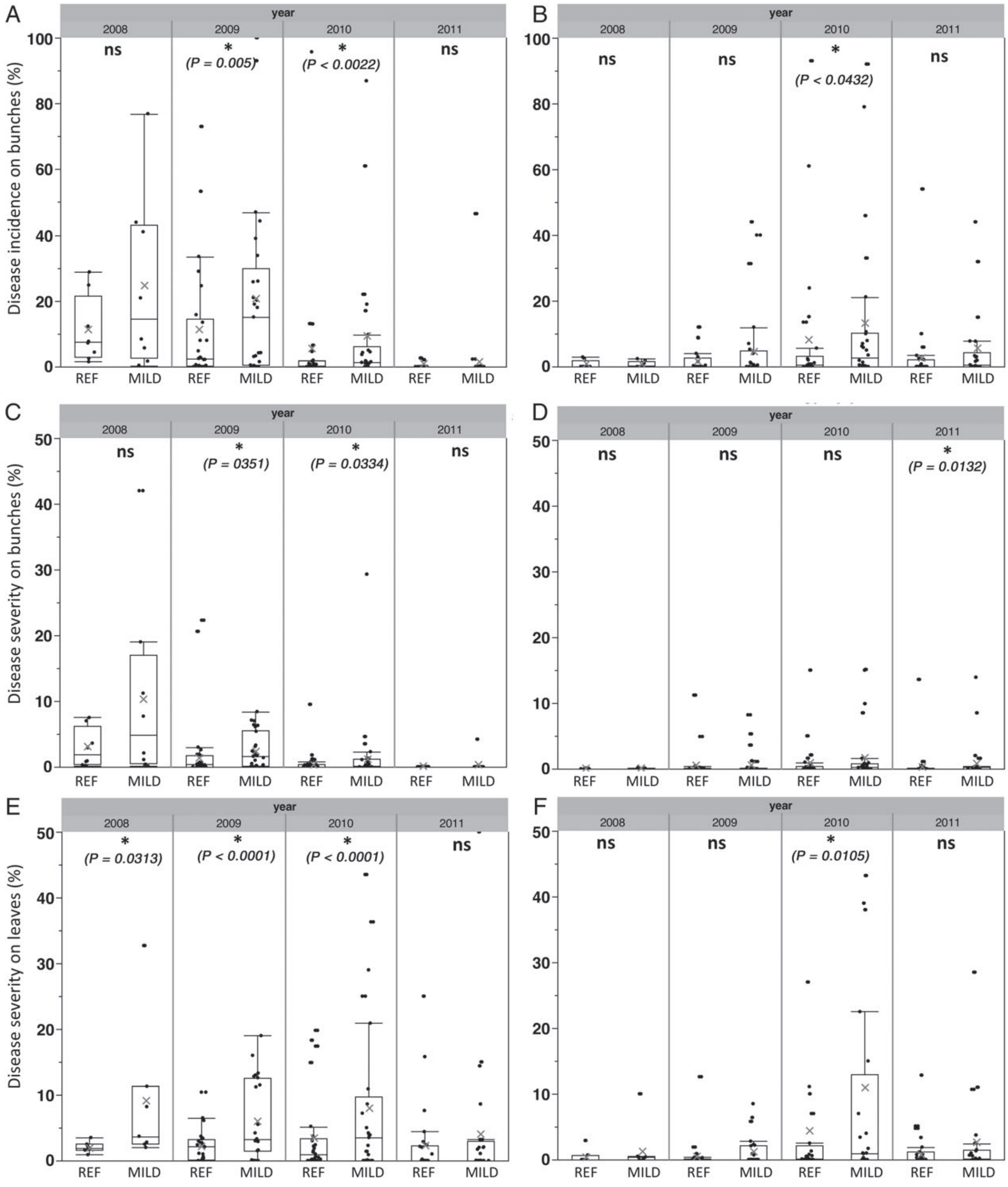


Figure 6. Distribution of disease incidence on bunches (A, B), disease severity on bunches (C,D) and disease severity on leaves (E, F) for downy mildew (A, C, E) and powdery mildew (B, D, F) for Mildium (MILD) and Reference (REF) blocks for each year. Combined box-and-whiskers plot and raw data. × denotes mean value of the data. The first and second whiskers are set to first quartile − 1.5*interquartile range and third quartile + 1.5*interquartile range respectively. An asterisk *denotes that the difference is significant (*P*-value for rank test); ns denotes that the difference is not significant.

can be observed only in 2011, but the mean spread is very small (0.5%).

Figures 6E and F analyse leaf protection performance. As regards downy mildew, leaf disease severity is higher on Mildium blocks (4–9%, compared with 2–4% for reference blocks), and the difference is significant for three of the four years of experiments (mean spread from 4 to 7%). As for powdery mildew, the differences in leaf protection are not significant except for the year 2010.

It should be noted that in the Atlantic and northern areas there is a discrepancy between reference and Mildium blocks for downy mildew, especially for disease incidence on bunches and disease severity on leaves. On the other hand, control of downy mildew was not an issue for Mildium in the Mediterranean area. The difference between regions was not surprising, but highlights the need for precaution and anticipation in the Atlantic and northern areas.

Table 3. Contingency table comparing the grower satisfaction with the Mildium strategy with the satisfaction with the reference strategy, assessed for three criteria and with a two-level score: 1 = grower satisfied; 0 = grower unsatisfied

		Mildium					
		Visual assessment		Yield		Grape quality	
Reference		1	0	1	0	1	0
1		73	9	77	5	78	4
0		0	1	0	1	0	1
TPR (%)[a]		88		94		95	
McNemar statistics	χ^2	7.11		3.2		2.25	
	P-value	0.008		0.073		0.13	

[a] True positive rate.

Regarding powdery mildew, bunch protection with Mildium is less satisfactory in the southern area but without significant difference between reference and Mildium blocks (supporting information Fig. Error! Reference source not found.).

3.4 Qualitative assessment by growers

Analysis of the satisfaction survey showed that TPR was high: 89, 94 and 95% for visual assessment, yield and grape quality respectively (Table 3). There were no false positives whatever the criterion. For the visual assessment, nine false negative cases were observed. In these cases the Mildium strategy was not sufficient to reduce the disease severity on bunches (downy mildew or powdery mildew – plots 4 and 1 respectively) or on leaves (four cases) as well as the reference strategy. This disease severity had an impact on yield in five plots and on grape quality in three plots. Results of the McNemar test indicated that the null hypothesis could not be rejected for these two criteria (Table 3).

4 DISCUSSION

4.1 Behaviour of the prototype decision system

In the experiments, the Mildium decision system led to significant TFI reduction (from 30 to 50%) of fungicides used against downy and powdery mildews, and that for all areas and years. We conclude that Mildium is robust in the sense that its behaviour with regard to the number of treatments is highly satisfactory for a wide set of phytosanitary conditions. The behaviour of Mildium was appropriate for both powdery mildew early symptom types: flagshoots and cleistothecia. In addition, Mildium has shown that it can cope with early downy mildew epidemics. Its behaviour is also satisfactory for epidemics of a very small magnitude, and the required treatments did not cause an excessive number of treatments.

This TFI reduction did not affect the harvest in 90% of cases, according to grower acceptance. Nevertheless, disease symptom levels (crop injury) are often higher with Mildium than with conventional crop protection, especially for downy mildew in the Atlantic and northern areas. It is worth recalling that crop injury does not lead in any case to crop damage, which is related to actual reduction in yield or harvest quality.[37]

For grapevines, some authors have shown that a slight increase in downy mildew injury on the leaf canopy did not result in loss of grape quality[38] owing to the capacity of the vine to compensate for a stress situation induced by downy mildew.[39] For powdery mildew, low levels of symptoms on clusters do not affect the organoleptic quality of wines.[40]

A few failure cases were encountered, which are described in the supporting information. The TFI reduction was no higher for these unsatisfactory situations than for satisfactory situations, and ranged from 7 to 60% for downy mildew and from 29 to 53% for powdery mildew.

As regards the 'secondary' diseases, especially *Guignardia bidwelli*, no injury was reported during the 4 years, either on Mildium or on reference blocks. With the Mildium prototype, *Guignardia bidwelli* is managed by the choice of fungicides used against downy and powdery mildew, especially by the required treatments with strobilurines and sterol biosynthesis inhibitor.

TFI reductions that do not lead to significant falls in crop protection performance may be obtained by other decision systems, and one major trend today is dose management. Compared with conventional practices, these dose management systems take into account the epidemic pressure as well as vegetation volume.[41–43] The Mildium method has the specific advantage of reducing the number of applications. This frees up manpower resources that may be reassigned by growers to more accurate observation of symptoms on the plots. Other advantages include cutting down equipment usage and fuel consumption. In addition, the Mildium design allows for future research and improvement such as dose management at certain periods, depending on bioclimatic conditions.

4.2 Formalising the common management of both mildews

Many growers use DSSs for their crop protection management. Yet rules for associating protection against both mildews are not specified in these DSSs, in spite of empirical evidence that resource management affects the decision and favours the association of two treatments in one application. Therefore, a decision to protect the crop against one disease often leads to the addition of a product targeted at the other disease. For conventional crop protection, this has high impact on the TFI, from preflowering to bunch closure.

During this susceptibility period, using the Mildium decision system, we can report the following results from the experiments on the network. If we consider the T1, T2, T4 and T5 applications: in 60% of cases, fungicides used against both mildews were mixed; in 25% of cases, only a product targeting downy mildew was sprayed; in 15% of cases, only a product targeting powdery mildew was sprayed. When a treatment was performed against one disease only, no case was reported of a second treatment targeting the other disease in a timeframe shorter than 10 days. This suggests that adequate planning as well as the formalisation of treatment association rules would make it possible to reduce the TFI significantly.

4.3 Qualitative values from adjustable thresholds

One major advantage of expressing a decision system using qualitative values, instead of thresholds based on fixed values, is the possibility for a user of this decision system to customise it to the particularities of a given plot or climate without compromising the expression of the overall strategy. Indeed, there is evidence that the relation between level of symptoms and actual injury is complex and varies according to, for example, cultivar.[1,44]

For easier data comparison across climatic regions and years, we have used fixed thresholds to determine the qualitative values in this experiment. Nevertheless, with the cropping system design in mind, the Mildium decision logics have been written so that they can be robust to threshold adaptation. Mildium is a prototype decision tool, and we can consider with Rabardel and Béguin[45] and the 'instrumental genesis' theory that users may involve some creativity of their own to adapt a tool to their own usage. The results obtained with Mildium with fixed thresholds on many plots and cultivars may be used as references for users of this research to find out threshold tunings that meet their needs. Besides adapting thresholds to users' own expertise and farming conditions, there are bioclimatic reasons that may motivate local adaptations. For example, there is still some debate between grapevine advisers of different regions about the ease of assessing early symptoms of powdery mildew on the leaves before flowering. Our data suggest that the relation between frequency of symptoms on leaves and frequency of symptoms later on bunches varies greatly, and that cultivars may differ from one to another in this regard. The definition of thresholds for powdery mildew would benefit from specific experiments in the northern area. In the southern area, cultivars such as Grenache and Carignan, for example, differ greatly. The latter frequently exhibits 'flagshoot' symptoms, while symptoms were mainly observed on bunches on the former. The use of the common thresholds for powdery mildew to cultivars susceptible to flagshoot symptoms, such as Carignan, appeared to trigger a conservative (high) number of treatments that was effective in obtaining good-quality grapes.

Overall, the Mildium decision system has proved to be very effective, at the plot level, with regard to its original objective, i.e. reducing the number of fungicide treatments on grapevine mildews while at the same time obtaining satisfactory protection for the grapevine. The DSS is able to provide decisions for each disease at seven stages in the season, with only three field assessments, owing to a design that interprets risk within a timely process and according to expertise on disease dynamics. We think that our design formalism may be applied to other pathosystems with multiple diseases. One important issue to be addressed to allow the practical application and adaptation of our system is the design of a decision support method at the farm level. This has implications for disease symptom detection methods and organisational issues, including implementing software at the farm and information systems, as well as economics and marketing.

5 CONCLUSION

The results of a 4 year assessment trial of the Mildium decision support system are very satisfactory. They show evidence that timely tactics for decisions at the plot scale, based on expertise of the diseases and predefined crop protection strategy, make it possible to reduce the number of treatments of downy mildew and powdery mildew compared with current practice, in various climatic conditions. We think that the Mildium prototype may encourage stakeholders to design customised farm-scale and low-chemical-input decision support methods.

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SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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