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Evaluation of a decision support strategy for the control of powdery mildew, *Erysiphe necator* (Schw.) Burr., in grapevine in the central region of Chile

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Abstract

BACKGROUND: The primary strategy to control powdery mildew in Chilean vineyards involves periodic fungicide spraying, which may lead to many environmental and human health risks. This study aimed to implement and evaluate the effectiveness and economic feasibility of a novel decision support strategy (DSS) to limit the number of treatments against this pathogen. An experiment was conducted between the 2010 and 2013 seasons in two irrigated vine fields, one containing a cultivar of Cabernet Sauvignon (CS) and the other a cultivar of Chardonnay (CH).

RESULTS: The results showed that the DSS effectively controlled powdery mildew in CS and CH vine fields, as evidenced by a disease severity lower than 3%, which was lower than that observed in untreated vines (approximately 10 and 40% for CS and CH respectively). The DS strategy required the application of only 2–3 fungicide treatments per season in key vine phenological stages, and the cost fluctuated between $US 322 and 415 ha^{-1}, which was 40–60% cheaper than the traditional strategy employed by vine growers.

CONCLUSION: The decision support strategy evaluated in this trial allows a good control of powdery mildew for various types of epidemic with an early and late initiation.

Keywords: vineyard; integrated control; grapevine disease; sustainable management

1 INTRODUCTION

The major disease known as 'powdery mildew' caused by *Erysiphe necator* affects vineyards worldwide and is undoubtedly the most important in Chile.[1,2] This disease accounts for most of the efforts and resources used by vine growers in their phytosanitary programs.[3–5] Under favourable weather conditions and without adequate control, powdery mildew may cause severe losses in yield and quality of the must and potentially affect the organoleptic quality of the wine.[6–13]

In the last 50 years, phytosanitary problems affecting vineyards have been managed primarily through the use of chemical products because they are relatively inexpensive and easy to obtain and spray. Chemical products have been proven to be very effective and reliable in large cultivated areas. Chilean vine growers primarily follow a 'zero risk' strategy with the purpose of harvesting grapes with no disease at all on the bunches.[14] This can be ensured by regular pesticide applications, regardless of the presence of disease. In Chile, vineyards managed in this way receive between 14 and 20 annual pesticide applications, 70% of which are fungicides against powdery mildew, depending on the grape cultivar and the geographical area. This type of strategy has also been employed in other regions of the world. For example, the average treatment frequency index (TFI), i.e. the number of applied pesticide doses per hectare per year, varied from 7.4 to 22.0 among French regions in 2006 and from 10.6 to 18.4 among German regions in 2007.[15]

The practice discussed above has resulted in an indiscriminate pesticide application in viticulture, which generates waste, and a number of national and international studies have demonstrated

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that it contaminates the surface and groundwater, thus threatening the flora and fauna and human health.[16,17] Furthermore, it is also important to note that the 'zero risk' management of powdery mildew can result in a significant increase in the proportion of pesticide-resistant pathogens.[10,18,19] This is the case for fungicides that inhibit sterol biosynthesis used against powdery mildew[20,21] or other more recent fungicides, such as QoI (azoxystrobin) and quinoxyfen.[22] Pesticide resistance is a serious problem because few chemical products can be used to control this important grape disease.

The facts stated above have led to criticism concerning the negative impact of chemicals on the environment and questioned the sustainability of this form of crop protection in most countries around the world. These concerns have resulted in the present constraint on European growers to reduce fungicide use according to European directives (i.e. Directive 1107/2009/EU). European governments currently enforce national action plans for pesticide reduction. Consequently, low-pesticide cropping systems based on innovative control methods need to be developed and evaluated. Therefore, the challenge is to move from a scheduled phytosanitary application strategy ('zero risk') to the rational management of pathogens based on their actual potential for crop damage.

Recently, many worldwide initiatives concerning integrated pest management (IPM) have used tools based mainly on empirical, weather-driven prediction models.[4,23] The degree-day model,[24] the grape powdery mildew risk assessment index[25] and the OiDiag system[26] are examples that pertain to powdery mildew. In Chile, only a couple of initiatives have been implemented to control powdery mildew by adapting predictive models to local conditions,[2,27] and promising results have been obtained in both cases. However, the use of models for decision-making has been discussed for several reasons:[28] (i) there are limitations due to the predictive quality of the models (i.e. how to estimate parameters and assess the models at farmers' fields, and specifically how to estimate conditions that favour a high primary inoculum level); (ii) in many cases, the models have not produced good results under all conditions; (iii) the gap between the representation of the world provided by a scientific model and the manner in which a farmer makes a decision.

A paradigm change arose from the simulation of the decision process itself and resulting practices,[29] and from the development of methods for capturing expert knowledge and formalising it into a model.[30] In this context, a novel decision support strategy (DSS) called Mildium® was proposed by plant pathologists during the last decade to rationalise fungicide application against powdery and downy mildew in grapevines.[31,32] This novel DSS is based on a new organisation of information-gathering and decision-making over time, and it translates the available epidemiological and expert knowledge into easily understandable rules for phytosanitary practitioners.[33] In general, the DSS is triggered by the following indicators: (i) epidemiological risk–climate models; (ii) observations of an attack in the vineyard; (iii) plant phenology; (iv) fungicide characteristics (e.g. the mode of action and the residual effect).[34]

Such a DSS was tested on a grapevine network of 83 plots in France during several consecutive seasons, which resulted in a decrease in spraying of 30–50% compared with traditional applications made by winegrowers in different growing regions, without increased damage to the grapes.[33,35]

In the central valley of Chile, the hot and dry weather during the day and the cool temperatures at night during the spring and the summer seems to be favourable for powdery mildew, even if the high level of radiance is unfavourable to the fungus – which is highly sensitive to UVB radiation[36] – but is favourable to the resistance of plant tissues.[37] Climatic characteristics in Chile could change the dynamics of the development of both the vine and the pathogen and therefore affect the efficiency of the DSS designed in France. In the present study, only the main algorithm for powdery mildew included in the DSS Mildium® was tested, and those for downy mildew or the interaction between both diseases were not considered. In this context, the study aimed to implement and evaluate the effectiveness and economic feasibility of the original decision support strategy for powdery mildew in grapevines cvs Cabernet Sauvignon and Chardonnay in the central region of Chile.

2 MATERIALS AND METHODS

2.1 Decision support strategy for powdery mildew control

The aim of the DSS is to limit the total number of treatments per year to 4. Therefore, two obligatory fungicide applications, at flowering and 12–14 days later (T1 and T2), are designed to protect the period of highest susceptibility on bunches. Two optional treatments would be triggered by an early detection of the disease on leaves (T0) or the presence of powdery mildew on the bunches 24 days after flowering (T3) (Fig. 1). The first treatment (T0) is a fungicide with preventive and curative effects to limit the growth of the fungus that might have started an infection period. The following treatments are renewed on the basis of field observations of disease development or by the observation of phenology (flowering-setting period). Thus, the DSS for powdery mildew was constructed to restrict the damage to the clusters to a threshold of 5% severity at harvest time[33] without consideration of its level on leaves.

To implement the DSS, three indices were recorded at different phenological stages as follows (Fig. 1):

1. The occurrence of signs on leaves was assessed visually for every 20 vines in the field (eight leaves per plant) at the growth stage of single flower separated [code 12 of the modified Eichhorn and Lorenz scale (E–L scale)].[38]
2. The occurrence of signs on clusters was evaluated by visually observing all clusters of approximately 40 vines per hectare at 24 days after flowering. This evaluation aimed to determine whether a new fungicide application was required subsequent to the two obligatory applications.
3. The persistence effect of the fungicide active ingredient was used to determine the maximum time required between the two treatments, according to the recommendation of the manufacturer.

2.2 Experimental field and cropping practices

The data were collected from the following two experimental fields: (a) a 1.60 ha vine field containing the cv. Cabernet Sauvignon; (b) a 1.66 ha vine field containing the cv. Chardonnay. Both fields are part of the Universidad de Talca's experimental vineyard (Maule Valley, Chile: 35° 22′ S, 71° 35.4′ W, WGS84, 121 m.a.s.l.). In the first experimental field, the study was conducted during the 2010–2011, 2011–2012 and 2012–2013 growing seasons, while it was carried out in the Chardonnay field during the 2011–2012 and 2012–2013 growing seasons only. The region is characterised by dry Mediterranean climatic conditions with an average annual rainfall of 692 mm, with more than 550 mm (80%) falling during the autumn and winter months, i.e. between April and September.

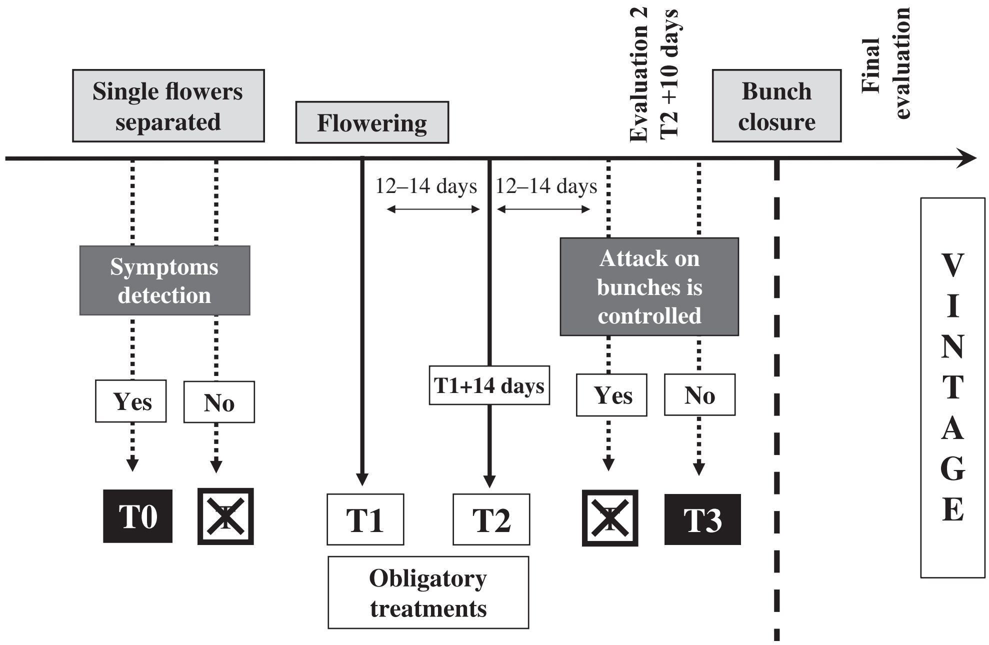

Figure 1. Decision support strategy (DSS) for the control of powdery mildew on grapevines (adapted from Delière *et al.*[33]).

The vineyard soil has a clay loam texture and an average slope of ∼1%, with two major soil series, namely the Talca (suborder Xeralf) and the San Rafael (suborder Xerol) series.[39] The Chardonnay and Cabernet Sauvignon fields were planted in 1994 and 1998, respectively, using own-rooted plants with a spacing of 1.5 m between the vines and 3.0 m between the rows which were oriented east to west. The vines were trained in a vertical shoot position system with a total height above ground of 2.0 m. Other characteristics of the vine fields were presented by Verdugo-Vásquez *et al.*[40] The vines were irrigated using furrow irrigation, as recommended by Acevedo-Opazo *et al.*[41] In the entire experimental vineyard, the shoots were topped and trimmed once a year. The vineyard was managed using standard agricultural practices for commercial vineyards in Central Chile (canopy management, fertilisation, pest and disease control, pruning and irrigation), which were similar throughout the three experimental seasons.

In the two experimental fields, two strategies to control powdery mildew were distributed in a block design with four replicates (0.20 ha each block) as follows:

1. The application of a DSS based on observations and the use of fungicides with preventive and curative effects, such as those in the group of strobilurins and triazoles. Thus, in T1 treatment we used azoxystrobin + difenoconazole (Amistar® Top SC, 0.065 kg AI ha^{-1}), in T2 treatment we used tebuconazole + trifloxystrobin (Consist® Full WG, 0.25 kg AI ha^{-1}) and in T3 treatment we used tebuconazole (Orius 43 EC, 0.18 kg AI ha^{-1}).
2. Reference reduced management (REF), normally used in an experimental vineyard, consists of a control based on the experience of the vine grower and prescheduled applications, using mainly preventive fungicides (sulphur) and also the same synthetic fungicides used in DSS, but with a maximum of nine treatments per season. Thus, this treatment involved seven or eight sprays per season of sulphur dust (0.18 kg AI ha^{-1}) and one spray of azoxystrobin + difenoconazole (Amistar® Top SC, 0.065 kg AI ha^{-1}) per season.

Untreated vines (eight plants per replicate) were untreated in each block to assess the disease pressure during each studied season. These vines were protected from the fungicide spray by wrapping the vines in a plastic film at the time of spraying. To control for mites, one or two treatments, depending on the season, were applied every year at the budburst and shoots 10 cm (five leaves separated) stages, by using mineral oil 99% (Citroliv emulsive®, 6 L ha^{-1}) and Acrinatrine (Rufast 75 EW®, 0.12 L ha^{-1}) in the entire experimental vineyard.

Finally, a survey was performed at ten major wine companies in the area to ascertain the crop protection practices of traditional vine growers (TVG). Their strategy consists of carrying out regular pesticide applications, considering only the persistence of the fungicide, regardless of the presence of disease. The fungicides used were sulphur and other ones in the group of strobilurins, triazoles, imidazoles, quinolines, etc. Thus, a phytosanitary programme for TVG was constructed, employing the fungicides most frequently used by them.

2.3 Field measurements

2.3.1 Meteorological measurements

These measurements were carried out to characterise the climatic conditions of the area and evaluate the potential primary contamination of powdery mildew. An automatic weather station (AWS) was installed on a grass cover at approximately 300 m from the experimental site. The AWS allowed the continuous measurement of wind speed, solar radiation, precipitation (rain gauge A730 RAIN; Adcon Telemetry, Klosterneuburg, Austria), temperature and relative humidity. Data were collected at 15 min time intervals and transmitted via a GPRS phone to the laboratory.

2.3.2 Disease assessments

Disease assessments were regularly performed on leaves and bunches to characterise the disease pressure (i.e. incidence and severity) that drives the DSS but also to evaluate its performance in controlling disease damage (Fig. 1). Thus, after the first evaluation (using the DSS) carried out at stage 12 of the Eichhorn and Lorenz phenological scale as modified by Coombe,[38] a new evaluation was repeated every 2 weeks up to the preflowering period (stage 18 on the E–L scale) on eight leaves per vine for approximately 115 vines per hectare, in one row for each three rows and one vine for each ten vines per row. After evaluation 2 in the DSS, new observations were carried out weekly on bunches and up to bunch closure on all bunches from 40 vines per hectare distributed in a regular grid. Finally, at veraison, a final observation was carried out to evaluate the performance of the treatments to control powdery mildew damage. The grapevine phenology stages were scored weekly on 30 shoots per plant with four plants per replicate throughout the experimental period as per Verdugo-Vásquez *et al.*[40]

2.3.3 Disease characterisation

To characterise the epidemic profile, the following three indices of disease damage were calculated on bunches from the untreated vines at veraison: (1) the average disease incidence and severity per vinestock; (2) the average severity of bunches with more than 10% severity per vinestock; (3) the number of vinestocks that had more than a quarter of bunches with >10% damage severity. A high level of damage on the bunches is a good indicator of the earliness of the attack on the leaves and consequently on the level of inoculum arriving early on the bunches. Vinestocks that have a high proportion of bunches with a high level of damage are likely the primary foci.[42] Furthermore, a powdery mildew latent period was calculated, as proposed by Calonnec *et al.*,[43] considering the time that wet conditions occur after budbreak as the onset of infection. This calculation allowed the determination of the number of powdery mildew cycles until the bunch closure stage.

2.3.4 Statistical analyses

Fisher–Pitman permutation tests[44] were first performed to compare the different indices two by two, and then to compare the severity of bunch populations of untreated vines versus DSS and DSS versus REF respectively (package coin of R statistical software v.3.1.2, function oneway_test with approximate distribution;[45] number of Monte Carlo redistribution 9999).

2.4 Economic analysis of crop protection strategies

A cost database was created for fungicide use, labour and machinery from the information collected from the survey mentioned above on traditional vineyard growers in the region, as well as information about the implementation of the REF and DSS strategies. This information allowed a cost comparison among the strategies to be carried out per item as follows:

(i) costs associated with the use of fungicides to control powdery mildew;
(ii) costs associated with the use of the tractor and hydropneumatic sprayer (rental and energy);
(iii) costs associated with the use of labour: the wages of the tractor driver performing the fungicide application and, in addition, for the DSS, the cost of monitoring powdery mildew which was carried out by a specialised technician.

3 RESULTS

3.1 Climatic and epidemic context

The climatic conditions during the three experimental seasons at the Panguilemo Experimental Station showed a typical pattern of a dry summer or Mediterranean climate (Table 1). In general, the average minimal and maximal temperatures during the different grapevine growth periods fluctuated in the range 6.8–11.2 °C and 21–29 °C respectively. For the 2011–2012 season, the maximal and mean air temperature, potential evapotranspiration (PET) and cumulative degree-days were higher than for other seasons throughout the budbreak to maturity period, but the precipitation was lower, particularly during budbreak and up to the flowering period. Consequently, the climatic water deficit (precipitation – PET) was higher in 2011–2012 (−931 mm) compared with the other seasons (lower than −830 mm).

Although early signs on leaves were not observed, an analysis of the disease data on bunches (at veraison) in untreated vines allowed a-posteriori analysis of the epidemic type. For Cabernet Sauvignon, the 2012–2013 season appeared less favourable for the disease, with significantly ($P < 0.05$) less disease incidence and severity on bunches (cf. Table 2). This is consistent with a late primary infection on the leaves, potentially around 20 October (Fig. 2). The two other seasons 2010–2011 and 2011–2012 were not significantly different, based on the disease incidence and average severity, and the level of disease on the bunches was consistent with early disease infection of leaves a few days before the 3–4-leaf phenological stage (13/10 for 2010–2011 and 6/10 for 2011–2012) (Fig. 2). The number of vinestocks with a high level of disease was higher for 2011–2012 because of a higher number of primary foci.

For Chardonnay, the most favourable year was 2012–2013 with a high level of disease incidence and severity and a high number of highly damaged vinestocks (Table 2). The results for this season are consistent with the very early infection of the Chardonnay leaves at the first rain following budbreak (Fig. 2), which was contrary to the Cabernet Sauvignon. The heavy rain that occurred on 2–4 October would have been unfavourable for primary infection of Cabernet Sauvignon.

3.2 Conduct of decision support strategy

In all of the modalities (year × cultivar), the disease was not found at phenological stage 12 on the leaves. Therefore, according to the DSS, the T0 treatment was never necessary. A T3 treatment was applied only in 2010–2011, even though the level of disease severity on the bunches was lower than 1.6%. Because the technical staff would not be available at the time of evaluation 2, the application of a possibly necessary treatment would be prevented (Table 3). In the REF treatment, 7–9 applications per season, irrespective of cultivar, were made, whereas in the DSS treatment the number of phytosanitary applications per season was reduced to 2 or 3 (depending on the season) compared with the REF treatment (Table 3). The differences were even greater when comparing the DSS with the traditional ‘zero risk’ (TVG) strategy, in which, irrespective of the season and the cultivar, the

Table 1. Summary of the main climatic variables that characterised the mean growing conditions for the Cabernet Sauvignon and Chardonnay cultivars during the 3 years of the study at the Panguilemo Experimental Station, Maule Valley[a]

Season	T_{max} (°C)	T_{min} (°C)	T_{mean} (°C)	DD (°C)	PET (mm)	Rain (mm)	PP – PET (mm)
2010–2011							
Budbreak-flowering	21.0	7.0	14.0	234	214	65	−149
Flowering-veraison	26.6	10.3	18.2	518	334	11	−323
Veraison-maturity	26.4	10.1	17.9	673	348	71	−277
2011–2012							
Budbreak-flowering	22.3	6.8	14.1	258	220	9	−211
Flowering-veraison	29.0	11.2	20.1	636	365	0	−365
Veraison-maturity	27.7	10.6	18.8	748	362	7	−355
2012–2013							
Budbreak-flowering	21.6	7.2	14.0	253	214	99	−115
Flowering-veraison	27.2	10.8	18.9	553	332	43	−289
Veraison-maturity	27.3	9.7	18.1	699	343	10	−333

[a] T_{max} – average maximum temperature; T_{min} – average minimum temperature; T_{mean} – average temperature; DD – cumulative degree-days (with a base of 10 °C); PET – potential evapotranspiration; rain – precipitation.

Table 2. Indices of disease damage calculated on bunches from the untreated vines at veraison during the three experimental seasons at the Panguilemo Experimental Station, Maule Valley. CH: Chardonnay, CS: Cabernet Sauvignon, SD: standard deviation

Cultivar	Year	Average incidence per vine (%)[a](SD)	Average severity per vine (%) (SD)	Bunches per vine with >10% severity (%) (SD)	Number of vines with highly diseased bunches[b]	Number of bunches observed
CS	2010–2011	62.4 (25.4) b	6.7 (5.4) b	15.5 (17.9) b	8 b	936
	2011–2012	55.2 (26.9) b	8.3 (10.5) b	23.7 (25.1) b	15 b	836
	2012–2013	34.1 (23.9) a	2.4 (2.9) a	4.7 (10.7) a	1 a	618
CH	2011–2012	56.3 (22.4) a	10.0 (12.4) a	28.2 (27.9) a	8 a	717
	2012–2013	89.5 (18.6) b	38.7 (30.6) b	66.5 (33.)7 b	27 b	777

[a] For each cultivar, values in the same column followed by different letters are statistically different (Fisher–Pitman permutation tests). All *P*-values were lower than 0.01.
[b] Number of vines with at least a quarter of bunches with >10% of disease severity.

growers performed an average of 14 fungicide applications per season.

If only two applications were made for DSS, they were mandatory, i.e. the applications at the growth stage of single flowers separated and between fruit set and bunch closure were not performed.

3.3 Incidence and severity of powdery mildew

No signs of disease were observed on leaves in the two vine fields in any season for the assessment at E–L stage 12 (which was included in the DSS) and also for the three other evaluations repeated every 2 weeks (up to E–L stage 18).

Evaluations carried out up to bunch closure showed a disease severity in the bunches that fluctuated between 0.02 and 0.6% for both vine fields during the 2011–2012 and 2012–2013 seasons, and it was 1.5% for 2010–2011 for Cabernet Sauvignon (data not shown).

At veraison, which was considered as the time when there was no further increase in observed disease both for cultivars and all seasons, the mean disease severity in bunches was significantly lower for the DSS and REF compared with the untreated vines ($P < 0.01$) (Fig. 3). The mean powdery mildew severity fluctuated from 0.1% (in the Cabernet Sauvignon field in the 2010–2011 season) to 2.1% (in the Chardonnay field in the 2012–2013 season) for DSS, but it was lower than 1.5% for all seasons for REF. The level of disease for DSS was not significantly different from the REF strategy. The final level of disease in both strategies was in accordance with the disease level in the untreated vines and the number of treatments applied.

3.4 Cost of protection against powdery mildew

When evaluating the total cost of the different strategies, we observed that the fungicide cost for REF and DSS was approximately 60–74% lower than the cost of the TVG strategy, i.e. a saving of \$US 215–280 ha^{-1}. In terms of machinery use, DSS was the least expensive compared with the REF and TVG. Figure 4 shows that DSS was 3–4 times less costly when compared with REF and 4–5 times cheaper than TVG. The DSS labour cost was the highest of the three strategies because it required more personnel for active monitoring of the presence of powdery mildew, with a labour cost/total cost ratio that fluctuated between 40 and 49%, depending on the number of assessments. REF was the least costly treatment in terms of labour cost of the three treatments, costing

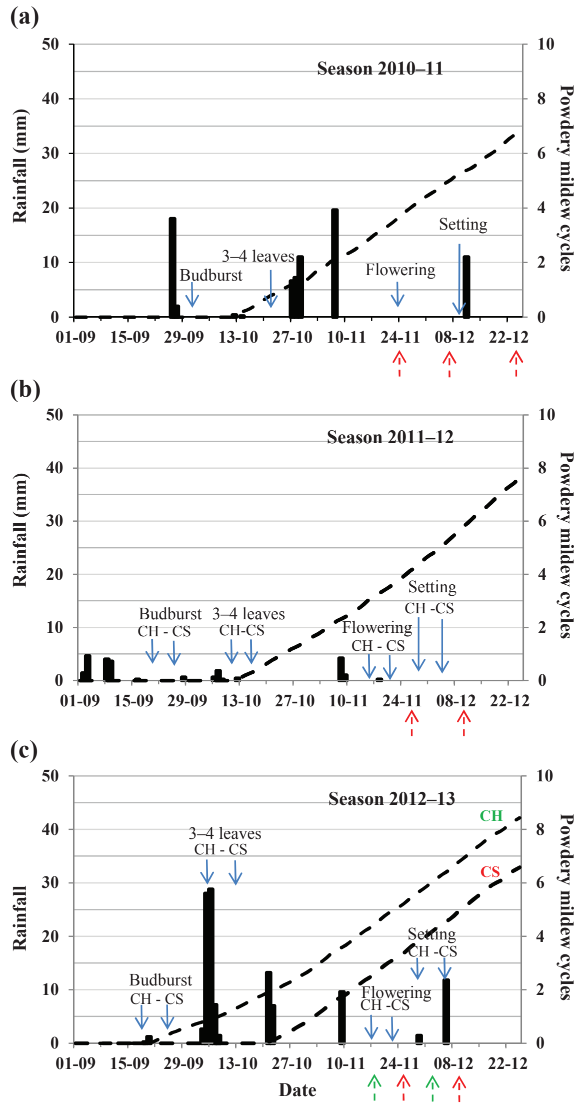

Figure 2. Rainfall (bars), main vine phenological stages (blue arrows) and powdery mildew cycles (dashed line) during the three experimental seasons at the Panguilemo Experimental Station, Maule Valley. CH: Chardonnay, CS: Cabernet Sauvignon. Dashed arrows correspond to fungicide applications.

roughly 3 times less than DSS, whereas the TVG labour cost was roughly double that of REF.

Table 3. Number of fungicide sprayings used in different powdery mildew control strategies. Reference reduced management (REF), decision support strategy (DSS) and crop protection practices of traditional vine growers (TVG). The TVG includes the mean and standard deviation of the survey performed in the wine companies

	Season		
	2010–2011[a]	2011–2012	2012–2013
Carbernet Sauvignon			
REF	8	7	9
DSS	3	2	2
TVG	14 ± 4	14 ± 4	14 ± 4
Chardonnay			
REF	–	8	9
DSS	–	2	2
TVG	–	14 ± 4	14 ± 4

[a] No experiments were conducted during the 2010–2011 season in the Chardonnay field.

4 DISCUSSION

4.1 Seasonal disease pressure

According to the damage observed in the untreated vines, and despite the fact that no disease was detected early in the season on the leaves, the control strategies could be evaluated for various types of epidemic. The damage observed in the Chardonnay field during the 2012–2013 season indicated early disease development. Humidity conditions (rain or fog) occurring between the vine phenological stages of budburst and four leaves separated could explain such an early powdery mildew epidemic which generated a high level of damage on the berries at harvest (∼39% severity on the berries).[42] Conversely, in the 2011–2012 season in the Chardonnay field and in all seasons in the Cabernet Sauvignon field, the disease severity in the untreated vines indicated a reduced disease development that did not exceed a mean value of 9%, consistent with late epidemic initiation. This difference in disease expression between the seasons and the vine fields can be explained by the interaction between the vine phenology and the climatic conditions and by the different disease susceptibilities in the experimental fields. The most dramatic differences were observed during the 2012–2013 season between the Chardonnay and Cabernet Sauvignon epidemics. The Chardonnay budded a few days before the Cabernet Sauvignon, and experienced more rain and humid conditions. In 2011–2012, the higher vigour and vegetative expression of Chardonnay compared with Cabernet Sauvignon could have been more conducive to powdery mildew development.[46] In this context, we can say that DSS captured the influence of climate and the interactions between the host and the pathogen.

4.2 Decision support strategy implementation

Even though Cabernet Sauvignon primary infections were thought to occur between 10 and 20 October in all seasons, we in no instance observed signs of disease on leaves at E–L phenological stage 12, so the T0 treatment was never applied in the DSS. This can be explained by fairly aggregated primary foci, and by the fact that sampling one in every 20 vines was insufficient, considering the difficulty of recognising signs on the leaves. Alternative ways to resolve this issue and provide greater security in the application of the DSS were to increase the sampling density (for example, one vine in ten) or to make the T0 fungicide application mandatory. On the other hand, the situation observed on Chardonnay in 2012–1013 corresponded to a high level of primary inoculum and early contaminations (high severity level on bunches for the untreated plots), significantly more conducive than 2011–2012. It was quite well controlled with the two obligatory treatments at and after flowering, even if the primary symptoms on leaves were not detected. An earlier treatment in T0 would have allowed even better control of the disease. Depending on the degree of 'exigence' of the grower, we could propose to add another screening on leaves, fitting with the end of the second cycle of the potential primary contamination (about 25 days after the first potentially effective rain). Symptoms on leaves are very tricky to detect, and it could be easier for the grower or technician to detect a second cycle.

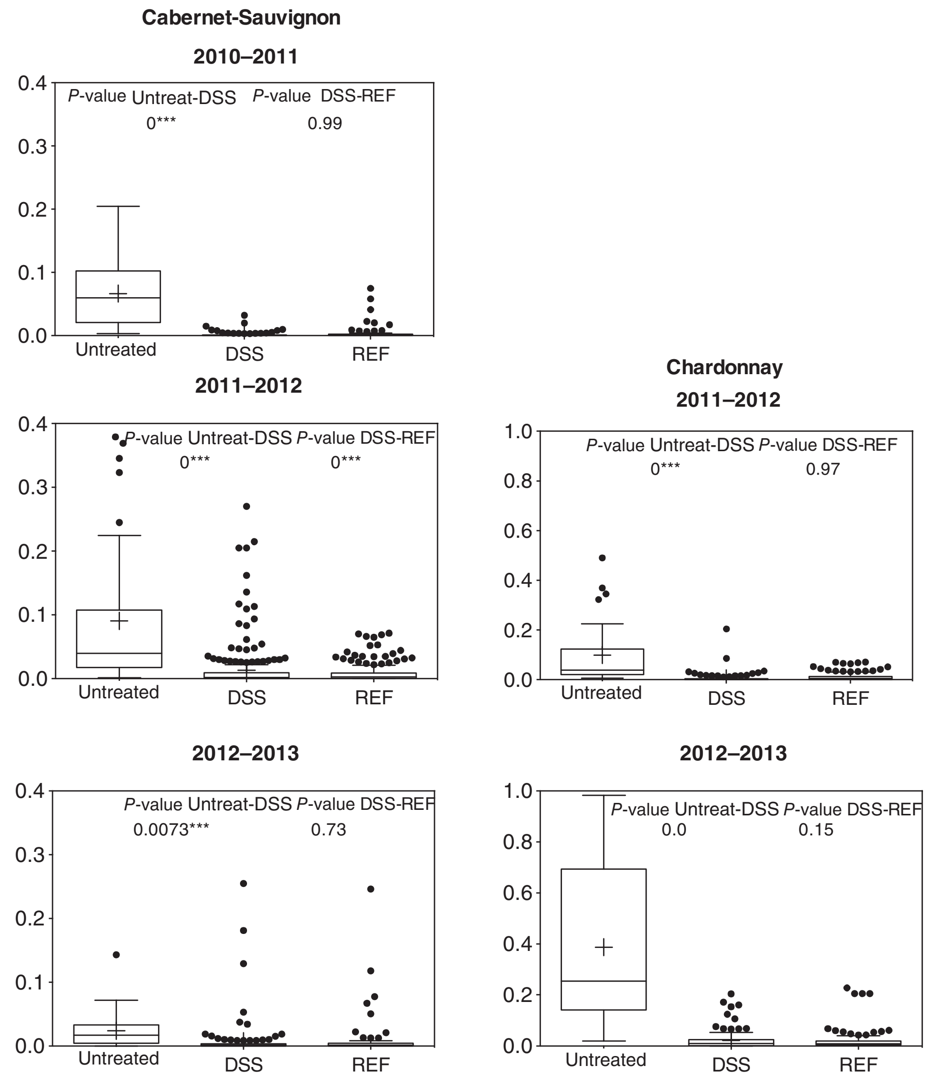

Figure 3. Box plot of disease severity on bunches for the three experimental seasons and two varieties Cabernet Sauvignon and Chardonnay. Reference reduced management (REF), decision support strategy (DSS) and untreated vines (Untreat). The + signs indicate the mean, and the box the 95% of data.

Mandatory applications during the flowering-setting period were the heart of the DSS. The timing of this application is key in disease control and requires a good estimate of phenology according to Verdugo-Vásquez *et al.*[40] This is especially true in highly heterogeneous fields characterised by topographical variations that influence the microclimate. Attention must be drawn to the importance of using representative zones in the field to estimate the flowering time, in order not to delay a fungicide application that could negatively impact on proper control of the whole field.

The T3 treatment in DSS was preventive during the first season in the Cabernet Sauvignon field, applied even if the level of disease severity on the sampled bunches was low (~1.5%). This decision was taken because the technical staff responsible for the application were to be on Christmas holiday at the time of evaluation 2, preventing the application of a potentially necessary treatment.

Although the T0 fungicide application was never performed and T3 was only applied once during the study period, the disease was well controlled, including Chardonnay. So, two or three fungicide applications could sufficiently control powdery mildew in the Mediterranean Chilean vineyards.

4.3 Adaptation of the DSS and REF to seasonal conditions

It was interesting to note that the vine grower changed his behaviour between years 1 and 2 by reducing the number of applications from 9 to 7 because of apparently less predisposing weather conditions and the success of the DSS. However, during the last season, he reverted to nine applications because the weather conditions were more predisposing with more rainy and cloudy days. This indicates how the vine growers adapt mainly to weather conditions that they observe, but because they do not have the tools to analyse the host–pathogen interaction, the fear that a major development of powdery mildew might occur causes the grower to overestimate the risk of reducing fungicide applications.

4.4 Behaviour of the decision support strategy

The number of phytosanitary applications per season was reduced from 7 to 9 in REF treatment to 2 or 3 in DSS. This reduction could be as high as 12 fewer fungicide sprayings in the DSS compared with the traditional strategy used by the vine growers in the region (TVG), which consisted of an average of 14 fungicide applications per season. The reduction in fungicide spraying did not affect

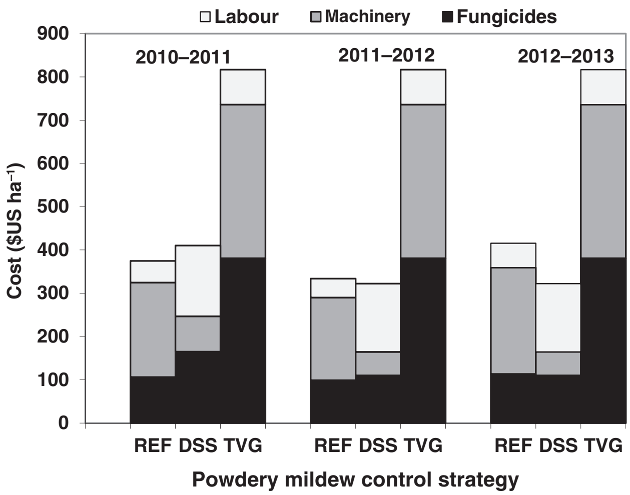

Figure 4. Cost (including labour, machinery and fungicides) of different powdery mildew control strategies ($US ha^{-1}) in the Cabernet Sauvignon field. Reference reduced management (REF), decision support strategy (DSS) and crop protection practices of traditional vine growers (TVG).

the yield or the quality of the harvest, as evidenced by a disease severity on the berries lower than 3% in all cases, which has been considered as a threshold value acceptable to the grower and discussed in the literature.[47] This value is even much lower than the threshold considered for quality damage of wine, which is indicated in some studies to be greater than 20%.[8] On the other hand, the behaviour of the DSS was appropriate for both early and late powdery mildew epidemics, as observed on non-treated vines.

We can conclude that the DSS is robust because it allows for successful control of powdery mildew with a reduced number of treatments for irrigated vineyards and ungrafted vinestocks under conditions that are very different from those under which it was developed and applied in France, as reported by Delière *et al.*[33] The climatic conditions were hot and dry during the day and cool at night during the spring, with the high level of UVB radiation that is characteristic of the region, and did not seem to counteract the development of the disease.[36] Despite the difference in the conditions of the grapevine system, the efficiency of DSS was proven.

4.5 Economic sustainability of DSS

The DSS is the least expensive of the three strategies in terms of a long-term policy. DSS is more expensive in terms of labour, but this additional cost is compensated by the strong reduction in operations and fungicide inputs. This last point is interesting considering that the cost of all production factors, manpower, fungicide and fuels (for machinery) have increased in the last decade. On the other hand, DSS must be gradually adopted by the vine growers before the maximum reduction in fungicides is achieved. It is difficult for the vine grower to break habits when it is used for systematic treatment, without observing first hand that reduction is possible.

This study demonstrated that DSS is an innovative technique for viticulture. This approach falls in line with the principal objectives of sustainable agriculture to optimise the principal resources in farming activities to secure the sustainable production of high-quality food and other products through ecologically preferable and safe technologies.[48] However, DSS must be improved on a vineyard scale. It has organisational issues linked to large areas; the average area of a vineyard in the central valley of Chile is approximately 14 ha, but vineyards exist that are 500 ha or greater. Relevant sampling at this scale must still be defined.

5 CONCLUSIONS

The DSS is robust because it allows for successful control of powdery mildew with a disease severity lower than 3% with a reduced number of treatments (2–3 applications per season) under conditions (i.e. irrigated vineyard and ungrafted vinestocks) very different from those under which it was developed and applied in France. The interactions between vine phenology, seasonal climatic conditions and different disease susceptibilities in the experimental fields allowed testing of the control strategies on various types of epidemic with early and late initiation. The level of damage at harvest on untreated berries under these conditions fluctuated on average from approximately 3% to 39% severity.

The cost per season for the REF and DSS treatments was similar and 40–60% cheaper compared with the traditional practice of the 'zero risk' strategy of regional vine growers (TVG), which consisted of an average of 14 fungicide applications per season.

The DSS evaluated in this trial provides an innovative technique to be used in sustainable vineyard systems.

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