Grapevine Downy Mildew: Long-term development and validation of plant protection strategies based on the forecast model "VitiMeteo Plasmopara"

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1 Introduction

Historical background

The State Institute for Viticulture and Enology (WBI, Freiburg, Germany), was founded in 1920 under the direction of Karl Müller. Karl Müller continued his earlier work on grapevine downy mildew (*Plasmopara viticola*) and dealt intensively with the conditions for the outbreak of the disease and the germination behaviour of the sporangia of the pathogen. His work provided precise data on the relationship between incubation time and temperature. Further studies on the development of oil spots and the formation of sporangia at the end of the incubation period also revealed a dependence of these events on temperature, humidity and time of day. The incubation curve created using these data has made the incubation calendar more precise. From now on it allowed the presentation of potential infection conditions as well as the prediction of the duration of the incubation period and dates of outbreaks based on weather observations. This was the first time that targeted treatments against grapevine downy mildew could be planned based on its biological development (Müller and Rabanus, 1923; Müller and Sleumer, 1934).

Research on grapevine downy mildew is still one of the main topics in plant protection at WBI. While the search for uncompromisingly safe control methods was at the forefront in the early days, today the focus is on safe protection of the grapevine with the minimum possible use of pesticides. Since the very first studies on grapevine downy mildew, the basic idea has always been: plant protection strategies achieve the best effectiveness when they take into account the biology of the pathogen. To this day, this idea shapes the work of WBI. Consequently, further studies from Freiburg and other institutes carried out during the 1920s, 1930s, 1970s (Blaeser, 1978) and 1980s (Gehmann, 1987) provided even more precise data on the relationship between weather conditions and the biology of downy mildew. At the end of the 1980s until the beginning of the 2000s, the first forecasting models were operated with small electronic weather stations. During this time, an intensive exchange about models took place on an international level, on the one hand at the Workshops on Grapevine Downy and Powdery Mildew and on the other hand at the IOBC (International Organisation for Biological Control) meetings.

Recent background

From the early and mid-2000s, the internet was used more intensively to provide model results. The precondition for the rapid dissemination of decision support systems was thus created. In parallel, the desire to reduce the use of pesticides grew in the European Community and in the individual member countries.

In consequence during the last years, plant protection in the EU and in Germany is increasingly influenced by new laws and regulations. The directive 2009/128/EC, for example aims for a sustainable use and a reduction of the risks and impacts of pesticides use in the European Community (EC) (https://ec.europa.eu/food/plants/pesticides/sustainable-use-pesticides_de). One tool for low pesticide use in crop protection is the Integrated Pest Management (IPM). IPM must be implemented by all professional users and promoted by EU countries, as specified in Annex III of the above-mentioned directive. Based on the directive, all EU countries developed own National Action Plans (NAP) for sustainable use of pesticides. An essential goal of the National Action Plan on Sustainable Use of Plant Protection Products in Germany (NAP Germany) is the reduction of pesticide treatments to necessary levels (https://www.nap-pflanzenschutz.de/en/about-the-national-action-plan/regulations/european-regulations/directive-2009128ec/ . Forecasting models, expert software and decision support systems are key factors to promote this process. A modern an intensively used platform for forecasting models, weather- and monitoring data for viticulture in the South-West of Germany (Baden-Wuerttemberg) is "VitiMeteo" (VM; www.vitimeteo.de). The basic science underlying the "VitiMeteo" platform has been continuously published (Bleyer *et al*., 2008; Bleyer *et al*., 2011; Bleyer *et al*., 2014, Bleyer *et al*., 2020a; Dubuis *et al*., 2012). The platform is a cooperative project between WBI, Agroscope (Changins, Switzerland) and the company GEOsens GmbH (Schallstadt, Germany). The working group is supported by other research institutes. Besides Baden-Wuerttemberg, Rhineland-Palatinate, Bavaria and Switzerland VM Models are widely used in other countries in Europe, such as France and Austria. "VM Plasmopara" was the first VM module, created in 2002. It calculates the most important steps of the infection cycle of downy mildew (Bleyer *et al*. 2008; Dubuis *et al*., 2012). The growth model "VM Growth", which was programmed for trellising systems in cooperation with H.-R. Schultz from Geisenheim University (Geisenheim, Germany) was the next component (Schultz, 1992). In 2004 "VM Growth" was implemented in the downy mildew model.

The weather forecast of the company Meteoblue (Basel, Switzerland) was embedded in the software modules since 2009. The integration of the weather forecast in all models was a milestone in the development of the system. This innovation allowed the calculation of incubation curves, total temperature, infection risk, leaf area and number of leaves as well as several other important parameters seven days in advance. On the basis of this implementation it was possible to make the first real predictions on plant protection applications in viticulture depending on weather conditions.

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During the past decades WBI has developed and established an effective growth- and model-based strategy to control grapevine downy mildew based on the calculations of "VitiMeteo". According to the current strategy, the effective period of fungicides is limited by the growth of the vines. Under permanent and heavy infection pressure 300 to 400 cm² of unprotected leaf area (corresponds to 2 to 3 new leaves) per primary shoot can develop before the next treatment is necessary (Bleyer *et al*., 2003). Since 2014 potassium phosphonate (Veriphos®) was registered as a fungicide in Germany. Four field trials were carried out between 2013 and 2016 to optimize the established strategy by use of this compound. The results showed that potassium phosphonate increases the effectiveness of the preventive fungicide "Folpet" in the three tested spray intervals of 400 cm², 600 cm² and 800 cm² leaf area per primary shoot (Bleyer *et al*., 2020). The results of the experiments also confirmed that it is possible to extend the treatment intervals from 400 cm² to 600 cm² leaf area, if potassium phosphonate was added to the preventive compound "Folpet". However, the combination is not sufficient under high infection pressure in intervals of 800 cm² leaf area per primary shoot (Bleyer and Lösch, 2017; Bleyer *et al*, 2020). The results of these studies allowed therefore a further optimization of the established strategy for grapevine downy mildew control (Fig. 1).

2 Materials and Methods

Validation under experimental conditions

The validation of the plant protection strategy of WBI against downy mildew of grapevine based on the forecasting model "VM Plasmopara" was carried out in two parts. The first part of the validation consisted of exact trials performed in accordance with the "EPPO-Guidelines for the efficacy evaluation of fungicides (*Plasmopara viticola*) (PP 113 1 (3))" and the principles of good experimental practice (GEP).
The optimized strategy was validated with four variants, which were tested between 2010 and 2021 as part of registration and demonstration trials.

The four tested variants were as listed below:

- **Untreated control**
- **"Folpet":** Continuous treatment with the preventive fungicide "Folpet" as a reference variant.
- **Strategy 1**: "Folpet" in combination with potassium phosphonate in the main growth phase (first application until BBCH 71-73).
- **Strategy 2**: Optimized application of different protective and curative fungicides with or without addition of potassium phosphonate depending on the infection pressure and the model outputs.

The trial vineyards were located in Freiburg and Ihringen (Germany) planted with the highly susceptible *Vitis vinifera* cultivars Mueller-Thurgau, Chasselas and middle susceptible cultivar Pinot noir. Artificial infections were performed on one leaf on every fourth vine at the BBCH-stages three unfolded leaves (BBCH 13) to six unfolded leaves (BBCH 16) (Lorenz *et al*., 1994). The first applications were conducted at the end of the incubation period. The following treatments were based on the optimized strategy for downy mildew control (Fig. 1). Spray treatments were performed with a tunnel-sprayer (Schachtner, Ludwigsburg, Germany) with TeeJet XR80015VS nozzles (TeeJet Technologies, Schorndorf, Germany). One aim of the studies was to identify the differences between the variants and to improve the strategy. Another was to create a balance sheet over a long period of time.

Validation under practical conditions

In parallel, the optimized strategy to control downy mildew was tested under practical conditions in Staatsweingut Freiburg, the model farm of WBI. Staatsweingut Freiburg cultivates a total area of roundabout 40 ha vineyards on three different locations. 32.4 ha (86%) are managed integrated and 5.2 ha (14%) with organic certification. The optimized strategy was evaluated in different vineyards at sites in Ihringen and Freiburg.
The two variants of the two trial locations are described below:

- **Untreated control (Ihringen):** a small-untreated plot of about 230 m².
- **Untreated control (Freiburg):** untreated control of the trials under experimental conditions mentioned above.
- **Strategy 2**: Optimized application of protective or curative fungicides with or without addition of potassium phosphonate depending on the infestation pressure and the model outputs.

The vineyards are planted with susceptible grape varieties typical for the site. The treatments against downy and powdery mildew were always carried out together with commercial crop protection sprayers. Treatments against powdery mildew were conducted according to OiDiag based on "VM Powdery Mildew" (Kast and Bleyer, 2010; Bleyer *et al*., 2013). Since 2020, "VM Powdery Mildew" has been significantly improved through the implementation of phenology models. Consequently, the susceptible time for infections on bunches are described much more accurately (Bleyer *et al*., 2020a).

3 Results

Validation under experimental conditions

During the twelve trial years, an average of eight applications were carried out during the seasons: minimum seven and maximum eleven. The average interval between two treatments was 11.4 days, with a minimum of seven days and a maximum of 17 days. The mean growth between two applications was four leaves and 470 cm² leaf area per main shoot; minimum was one leaf and 50 cm² leaf area / main shoot, maximum was seven leaves and 1300 cm² leaf area / main shoot.
All twelve trials between 2010 and 2021 showed sufficient infestation to produce reliable data. The severity of grape infestation of the untreated control was used as a measure of infection pressure. On average, it was classified as strong and reached 60.5 % (Table 1). The trials showed that strategies 1 and 2 had better effects on both leaves and grapes than the reference variant „Folpet". However, significant differences between „Folpet", strategy 1 and strategy 2 were only observed in the years with very high infection pressure, such as 2010, 2012, 2016 and 2018. Only in season 2016 strategy 1 showed a considerably worse effect than strategy 2. A remarkable result is also that the preventive „Folpet"-variant

showed a grape infestation of less than 10 % severity in eight out of twelve trial years. Disease severity of leaves was below 10 % in nine out of twelve years.

Validation under practical conditions

Location Ihringen

On average, eight applications were performed during the seasons of the ten observed years (2011-2021); minimum seven and maximum ten. The median interval between two treatments was 12.5 days; minimum was six days and maximum was 33 days (data not shown). The evaluations in the various vineyards in Ihringen showed no economically relevant infestation with downy or powdery mildew in any of the years.

Location Freiburg

On average, eight applications were carried out in the eight years of the study (2014-2021), with a minimum of seven and a maximum of ten. The mean interval between two treatments was twelve days; the minimum was seven days and the maximum was 33 days (data not shown). The assessments in the different vineyards in Freiburg presented also no economically relevant infestation with downy or powdery mildew in all years.

4 Discussion

Trials under experimental conditions

The results of the trials showed that only in years with high infection pressure the continuous use of the preventive fungicide "Folpet" is not sufficient for successful control of downy mildew. However, it was clearly demonstrated that a reduction of an economically significant downy mildew infestation is possible with both strategy 1 and strategy 2.

Especially strategy 1, “Folpet” in combination with addition of potassium phosphonate in the phase of main growth, is a strategy that is easy to implement for winegrowers. One of the main advantages of this strategy is that both active ingredients are not at risk of resistance development. Strategy 2, optimized application of protective or curative fungicides with or without addition of potassium phosphonate depending on the infestation pressure and the model results, is the safest way to prevent downy mildew infestation.

Trials under practical conditions

The evaluations in the different vineyards at the two locations Ihringen and Freiburg clearly showed that strategy 2 can prevent an economically significant infestation with downy mildew under practical conditions. The data also showed that the combination of model-based strategies against downy mildew and powdery mildew can be successfully combined. No economically important infestation of powdery mildew was detected during the experiments.

The long-term summary of both the experimental and the practical investigations demonstrate that strategy 2 can be very well recommended to viticulture practice.

5 Conclusions

The studies presented in this work clearly demonstrate the possibility to implement the requirements of directive 2009/128/EC and the National Action Plan on Sustainable Use of Plant Protection Products in Germany (NAP Germany) in practice. The requirements of IPM can be successfully fulfilled with the presented model-based strategies. The data shows that applications can be highly adjusted and targeted dependent on infection pressure. By application of the presented strategies, regular calendar applications of plant protection products are avoided. Thus, it is possible to save treatments in some years. However, before applying crop protection products, winegrowers must consider other ongoing work in the vineyard, such as foliage work in the vines, to optimize the application of plant protection products. This is often difficult and requires a high degree of flexibility. Therefore, constant training is essential for winegrowers to successfully apply the strategies presented. In principle, knowledge transfer is the key for the practical implementation of the requirements of IPM in the vineyard. Training and transfer of knowledge into practice is provided in many ways at WBI: by education, study, conferences, seminars, publications as well as online via www.vitimeteo.de. In particular, WBI has been organising “VitiMeteo” seminars for 20 years.

In the future, “VitiMeteo” will continue to be constantly developed and adapted to changing conditions. For example, new tools for calculating the effective period of a treatment against downy mildew and powdery mildew are currently under development. From the beginning of the season in 2022, the new tools will be released on www.vitimeteo.de, allowing advisors and winegrowers to easily determine the time span until the next treatment. For organic viticulture in particular, this tool can help to safe yields by also taking into account wash-off effects of cupper fungicides due to precipitation. The new decision tools are intended to digitally support advisors and winemakers in the practical implementation of model-based strategies

One of the main advantages of the "VitiMeteo" internet platform is that the two research institutes own the software, so "VitiMeteo" is independent of commercial interests. Another key advantage is the open architecture of information technology of the "VitiMeteo" system, which allows programming new models (e.g., new diseases and pests) and new functions. The "VitiMeteo” system" will continue to be a variable, interactive system for scientists, advisors and winegrowers.

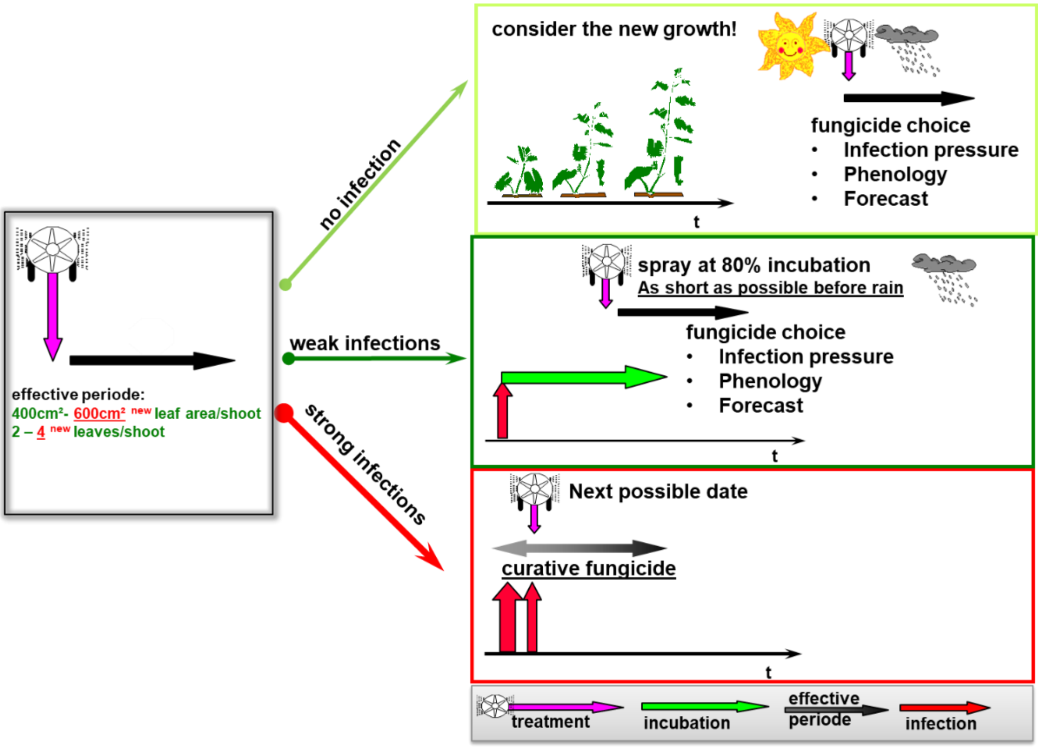

Figure 1. Plant protection strategies of the State Institute for Viticulture and Enology in Freiburg (Germany) against downy mildew of grapevine based on the forecasting model "VitiMeteo Plasmopara” (status 2022)

location / year	*infection pressure*	*number of treatments*		*untreated control*		*Folpet*		*strategy 1*		*strategy 2*	
		pb-b-ab	total	leaf infestation severity	grape infestation severity	leaf infestation severity	grape infestation severity	leaf infestation severity	grape infestation severity	leaf infestation severity	grape infestation severity
Ihringen, Bl`berg 2021	3	3 _ 1 _ 4	8	43.7 A*	73.3 A	8.5 B	8.5 B	3.3 B	2.2 B	2.8 B	1.8 B
Freiburg 2020	1	2 _ 1 _ 4	7	21.7 A	13.0 A	0.4 B	0.3 B	0.5 B	0.3 B	0.5 B	0.2 B
Freiburg 2019	4	3 _ 1 _ 4	8	30.8 A	86.6 A	3.2 B	2.6 B	1.0 B	0.6 B	1.0 B	0.7 B
Freiburg 2018	4	3 _ 1 _ 4	8	40.8 A	88.5 A	6.4 B	19.5 B	5.1 B	10.3 BC	2.5 B	0.4 C
Ihringen, Bl`berg 2017	1	2 _ 1 _ 4	7	43.6 A	12.0 A	2.3 B	0.0 B	1.9 B	0.1 B	2.1 B	0.0 B
Freiburg 2016	4	3 _ 1 _ 4	8	36.9 A	98.6 A	2.4 B	16.4 B	1.7 B	1.8 C	1.1 B	0.2 C
Freiburg 2015	2	3 _ 0 _ 4	7	12.9 A	29.9 A	1.5 B	0.9 B	0.3 B	0.1 B	0.6 B	0.2 B
Freiburg 2014	2	3 _ 1 _ 4	8	9.4 A	20.0 A	0.0 B	0.0 B	0.0 B	0.0 B	0.0 B	0.0 B
Freiburg 2013	4	3 _ 1 _ 4	8	49.8 A	82.5 A	10.0 B	0.1 B	1.6 B	0.0 B	3.5 B	0.0 B
Freiburg 2012	4	3 _ 2 _ 6	11	52.7 A	100.0 A	11.6 B	57.8 B	1.4 C	1.8 C	0.5 C	0.4 C
Ihringen, Bl`berg 2011	2	2 _ 1 _ 4	7	26.5 A	21.9 A	1.0 B	0.1 B			1.0 B	0.1 B
Freiburg 2010	4	3 _ 1 _ 5	9	41.0 A	99.7 A	11.8 B	36.0 B			5.9 C	12.2 C
Ø 2010 - 2021	3		8	34.1	60.5	4.9	11.8	1.7	1.7	1.8	1.4

Table 1. Validation of the plant protection strategy of the State Institute for Viticulture and Enology in Freiburg against downy mildew of grapevine based on the forecasting model "VitiMeteo Plasmopara”.
pb-b-ab: **pre** **b**loom, **bloom**, **a**fter **b**loom; strategy 1: “Folpet“ in combination with potassium phosphonate till BBCH 71-73; strategy 2: application of protective or curative fungicides with or without potassium phosphonate depending on the infestation pressure; “Folpet” (Folpan WDG®), Pp = potassium phosphonate (Veriphos®)
A*: different letters indicate significant differences between the treatments (one-way ANOVA; $p \leq 0.05$)
Infection pressure was characterized by severity of grape infestation; 0 = 0 %, 1 weak = 1- 20 %, 2 medium = 20-50 %, 3 strong = 50-80 %, 4 very strong =80-100 %

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