

**Metrafenone resistance in a population of *Erysiphe necator* in northern Italy**

Andrea Kunova, Cristina Pizzatti, Maria Bonaldi and Paolo Cortesi<sup>1</sup>

Department of Food, Environmental and Nutritional Sciences, University of Milan, Via  
Celoria 2, 20133 Milan, Italy

<sup>1</sup>Corresponding author: Paolo Cortesi, Department of Food, Environmental and Nutritional  
Sciences, University of Milan, Via Celoria 2, 20133 Milan, Italy, E-mail:  
[paolo.cortesi@unimi.it](mailto:paolo.cortesi@unimi.it)

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/ps.4060

**ABSTRACT**

**BACKGROUND:** Metrafenone has been used in Europe in integrated pest management programs since 2006 to control powdery mildews, including *Erysiphe necator*. Its exact mode of action is not known, but it is unique among fungicide classes used in powdery mildew management. Recently, resistance to metrafenone was reported in *Blumeria graminis* f.sp. *tritici*. In this study we investigated metrafenone resistance in *Erysiphe necator* in northern Italy.

**RESULTS:** Metrafenone efficacy to control grapevine powdery mildew was monitored in three consecutive years in field, and its reduced activity was observed in 2013. Out of thirteen monoconidial isolates, two sensitive strains were identified, which did not grow at fungicide concentration recommended for field application. The remaining strains showed variable response to metrafenone, and five of them grew and sporulated similarly to control even at 1250 mg L<sup>-1</sup> of metrafenone. Moreover, the resistant strains showed cross-resistance to pyriofenone, which belongs to the same FRAC group as metrafenone.

**CONCLUSION:** The results indicate the emergence of metrafenone resistance in an Italian population of *Erysiphe necator*. Further studies are needed to get an insight into the metrafenone's mode of action and to understand the impact of resistance on changes in the pathogen population structure, fitness and spread of resistant strains, which will be indicative for designing appropriate anti-resistance measures.

**KEYWORDS:** *Uncinula necator*, *Oidium tuckeri*, fungicide resistance, benzophenone, pyriofenone, *Vitis vinifera*

## 1 INTRODUCTION

Grapevine powdery mildew, caused by the obligate biotrophic fungus *Erysiphe necator* Schwein. (previously *Uncinula necator* (Schwein.) Burrill; anamorph *Oidium tuckeri* Berk.), is one of the most important fungal pathogens of cultivated grapevine worldwide.<sup>1,2</sup> It infects all green parts of the plant, such as leaves, shoots, flowers and fruit clusters.<sup>2,3</sup>

The control of *E. necator* in Italian vineyards follows principles of integrated pest management (IPM), which combines the use of chemicals with agronomical practices.<sup>4</sup> However, the use of fungicides remains the main and the most effective means to control powdery mildew epidemics. They are usually applied in preventive programs. The treatments start as early as 3-5 leaf stage of shoot development (BBCH stage 13-15) if the epidemic risk is high and associated with pathogen overwintering in dormant buds or conditions favorable for ascospore infections, and continue until grape veraison (BBCH stage 81-83), which implies minimum of 4-8 fungicide treatments during the growing season.<sup>5</sup>

Fungicide Resistance Action Committee (FRAC) classified commercial fungicides into different groups based on their mode of action.<sup>6</sup> The majority of modern fungicides have a single-site mode of action, which highly increases the risk of resistance in diverse pathogen populations. Therefore, their use is limited to 2-3 applications per season, which implies the availability of a large number of different fungicide groups. In Italy, fungicides belonging to 10 different FRAC groups are currently on the market to control grapevine powdery mildew in conventional agriculture.

*E. necator* is listed as a medium risk pathogen by FRAC, but as a high risk pathogen by the European and Mediterranean Plant Protection Organization (EPPO).<sup>7</sup> It developed resistance to several fungicide groups, including methyl benzimidazole carbamates (MBC, FRAC group 1), demethylation inhibitors (DMI, FRAC group 3), aza-naphthalenes (FRAC group 13) and quinone outside inhibitors (QoI, or strobilurins, FRAC group 11).<sup>8-13</sup> In case of QoIs and

DMIs, the main molecular mechanisms of their modes of action are known and diverse mutations responsible for the resistance were already described.<sup>10,14-16</sup>

However, identification of resistant isolates does not always lead to field resistance.<sup>17</sup> To prevent or delay the selection and spreading of resistant isolates in the pathogen population, implementation of appropriate anti-resistance management strategies is of utmost importance.

One of the key strategies is the rotation of fungicides with different modes of action.<sup>18</sup>

Metrafenone (3-bromo-2',3',4',6-tetramethoxy-2,6'-dimethylbenzophenone) is a fungicide active against diverse powdery mildews including grapevine powdery mildew. It is representative of the chemical class benzophenones, and together with a benzoylpyridine pyriofenone belongs to the U8 FRAC group.<sup>6</sup> Its exact mode of action is not known, however, early studies on barley powdery mildew (*Blumeria graminis* Speer f. sp. *hordei* Marchal) and wheat powdery mildew (*Blumeria graminis* Speer f. sp. *tritici* Marchal) suggest that it interferes with hyphal morphogenesis, polarized hyphal growth and the establishment and maintenance of cell polarity.<sup>19,20</sup> Metrafenone has a unique mode of action, different from other fungicides used in powdery mildew management as demonstrated by absence of cross-resistance with other known chemical classes, and therefore it represents a valuable choice in fungicide rotation programs.<sup>14,19,20</sup> Recently, metrafenone-resistant isolates of *B. graminis* f.sp. *tritici* were detected in an extensive monitoring study of cereal powdery mildews, however its performance in field was not reduced.<sup>21</sup> Until now, this is the only report of reduced efficacy of metrafenone in field.

Our objective was to verify the efficacy of metrafenone to control grapevine powdery mildew pathogen, *E. necator*, after 8 years of its extensive use in Italian vineyards. For this purpose we monitored the efficacy of metrafenone to contain powdery mildew epidemics in a vineyard in Timoline (BS), in northern Italy, in three consecutive years. Furthermore, we determined the response of *E. necator* isolates, collected subsequently from the experimental

vineyard, to elevated concentrations of metrafenone in terms of mycelium growth and sporulation. Finally, we monitored the presence of metrafenone-resistant isolates in the Franciacorta area in 2013 and 2014.

## 2 MATERIALS AND METHODS

### 2.1 Disease epidemics and metrafenone activity in field

Biological activity of metrafenone was assessed in a vineyard in Timoline (Franciacorta area, Italy), during the years 2011-2013. The vineyard was planted with *Vitis vinifera* cultivar 'Chardonnay', cordon trained and spur pruned, with a planting density of 6250 plants ha<sup>-1</sup>.

The experimental scheme consisted of randomized blocks with four replicas and each plot included 12 plants grown on a surface of approximately 18 m<sup>2</sup> (8.8 x 2 m). Downy mildew was managed using Forum MZ (BASF, 9.0 g ha<sup>-1</sup> dimethomorf + 60.0 g ha<sup>-1</sup> mancozeb) and Pergado MZ (Syngenta, 50 g L<sup>-1</sup> mandipropamid + 600 g L<sup>-1</sup> mancozeb), applied at the rate of 220 and 250 g ha<sup>-1</sup>, respectively.

To assess the biological activity of metrafenone, Vivando (BASF, 500 g L<sup>-1</sup> a.i.) was applied preventively, before the appearance of powdery mildew symptoms, starting from the BBCH stage 13-15 (3-5 fully unfolded leaves), at the rate 250 ml ha<sup>-1</sup> with the interval of 10-12 days. The disease progress in the untreated control and in metrafenone-treated plots was monitored periodically from bud-break to veraison by inspecting 100 leaves or grape clusters for plot.<sup>22</sup> The disease incidence (DI) was expressed as percent of infected leaves or grape clusters. The disease severity (DS) was calculated according the Townsend-Heuberger formula,<sup>23</sup> using eight classes of severity index based on the surface of the organ colonized by the pathogen. Subsequently, protection indices for disease incidence and severity were calculated.<sup>24</sup>

## 2.2 Sample collection and maintenance of *E. necator* strains in laboratory

In 2013, infected leaves and grape clusters were collected from the vineyard in Timoline (BS) from the untreated control and metrafenone-treated plots, and ten monoconidial isolates were obtained in laboratory (Table 1). Three additional monoconidial isolates of *E. necator* were obtained from a commercial vineyard in the Franciacorta area, distant 2.5 km from the Timoline vineyard, to verify if the metrafenone resistance is more widely spread in the area. The infected tissues were observed under the dissecting microscope and single-conidial chains were transferred from the infected leaf to a newly formed leaf of *V. vinifera* cv. ‘Chardonnay’ grown in laboratory as described previously.<sup>25</sup>

In 2014, the vineyard in Timoline changed from IPM to biological management, and the use of synthetic fungicides was discontinued. Powdery mildew-infected leaves were collected, and single conidial-chains from sporulating colonies of *E. necator* were directly transferred on leaves preventively treated with metrafenone (125 mg L<sup>-1</sup>) or non-treated leaves, and incubated in Petri plates containing water-agar medium (8g L<sup>-1</sup> agar bacteriology grade, Applichem) added with 5 mg L<sup>-1</sup> of tetracycline. The growth of resistant isolates was verified after two weeks of incubation in a growth chamber with 16h day cycle at 24°C.

The strains were routinely maintained on leaves of *V. vinifera* plants, cv. ‘Chardonnay’, grown from seeds in laboratory conditions. Leaves from 4-5-week-old plants were surface sterilized for 15 sec. in 70% ethanol and 1 min in 0.5% hypochlorite and rinsed 3-times in sterile water. Leaves were dried by paper tissues and placed in Petri plates containing water-agar medium. The plates were cultivated in a growth chamber with 16h day cycle at 24°C. Strains were transferred to fresh leaves every two weeks.

### 2.3 Mycelium growth and sporulation of *E. necator* exposed and non-exposed to metrafenone in laboratory

The strains of *E. necator*, collected in 2013, were grown for two weeks as described previously to sporulate abundantly. Four-week-old plantlets of *Vitis vinifera* cv. 'Chardonnay' were sprayed with two different concentrations of metrafenone: 125 mg L<sup>-1</sup> (field treatment concentration) or 1250 mg L<sup>-1</sup> (10-times field treatment concentration) and were left to air-dry for 2 hours. Control plants were sprayed with water. The plants were subsequently inoculated by depositing spores of *E. necator* on the two youngest leaves on 4 points/leaf. The inoculated plants were incubated for two weeks, and the mycelium growth was assessed 14 days after inoculation. The colony growth was estimated by transferring the dimensions of the colony observed under the dissecting microscope to a millimeter graph paper and then calculating the colony area using the program ImageJ.<sup>26,27</sup> Sporulation was evaluated 14 days after inoculation: the entire colony was cut out and put in an Eppendorf tube containing 100µl of 0.9% NaCl + 0.02% Tween 80 and number of conidia µl<sup>-1</sup> was counted with haemocytometer after vortexing. The sporulation (Sp) was expressed as conidia cm<sup>-2</sup>;  $Sp = N * 100 / A_{14}$ , where N- number of conidia µL<sup>-1</sup>, A<sub>14</sub> - area of the colony 14 days after inoculation. The experiments were repeated two times.

### 2.4 Cross-resistance

We studied the cross-resistance of *E. necator* metrafenone-resistant strains to pyriofenone (90 mg L<sup>-1</sup>, Kusabi, Belchim), a fungicide belonging to the same U8 FRAC group. Moreover, we tested two additional fungicides widely used in powdery mildew management, belonging to QoI and DMI groups; azoxystrobin (175 mg L<sup>-1</sup>, Quadris, Syngenta) and myclobutanil (60 mg L<sup>-1</sup>, Thiocur Forte, Dow AgroSciences), respectively. All fungicides were tested at recommended concentrations for field application. One metrafenone-sensitive strain (2C) and

two resistant strains (1M and 2M) of *E. necator* were grown for two weeks to sporulate abundantly as described previously. Four-week-old plantlets of *Vitis vinifera* cv. 'Chardonnay' were treated with the recommended field concentrations of the above-listed fungicides, or metrafenone (125 mg L<sup>-1</sup>) and were left to air-dry for 2 hours. Control plants were treated with water. The plants were subsequently inoculated with spores of *E. necator* using an inoculation tower and air-current. Inoculated plants were incubated in a growth chamber for 12-14 days, and the disease severity was determined by estimating the % of leaf surface colonized by sporulating colonies of *E. necator*. The experiments were repeated two times.

## 2.5 Statistical analyses

The statistical analyses were performed using R software, version R3.0.2.<sup>28</sup> The percent data of disease incidence and disease severity in control and metrafenone-treated plots were root-square arcsine transformed and submitted to ANOVA. Similarly, ANOVA was performed for mycelium growth and sporulation data, followed by a Tukey post hoc test for multiple comparison ( $P = 0.05$ ), using the TukeyC package.<sup>29</sup>

## 3 RESULTS

### 3.1 Powdery mildew epidemics in 2011-2013

During the three years of the study in Timoline field, the dynamic of powdery mildew epidemics was variable. The disease dynamic was monitored in the control plots from bud break (mid-April) to veraison (mid-July) (Figure 1). The 2011 season was characterized by conditions unsuitable for disease development. The disease progress was slow resulting in 8% of grape clusters infected in mid-July, while the disease was almost absent on leaves. In 2012, the first symptoms appeared at the end of May and afterwards the disease incidence

increased constantly. In mid-July, almost 100% of grape clusters and ca. 60% of leaves were infected with a disease severity index ca. 50%. In 2013, disease incidence had the fastest progress and in mid-July, almost 90% of leaves and 100% of grape clusters were infected.

### **3.2 Biological activity of metrafenone in field**

The powdery mildew incidence and severity were evaluated on leaves and grape clusters of control plots and plots treated with metrafenone in mid-July in 2011-2013 and the respective protection indices were calculated (Figure 2). Control plots were heavily infected in 2012 and 2013, with the disease particularly serious on grape clusters, while it was sporadic in 2011.

In 2011, metrafenone showed 100% efficacy on leaves and 93.5% and 98.7% protection of grape clusters in terms of disease incidence and severity, respectively. In 2012, metrafenone protected grape clusters by 52.2% (DI) and 84% (DS) compared to control, and showed even better protection on leaves. Finally, the 2013 season was even more favorable for disease epidemic development, with approximately 90% of leaves and 100% of grape clusters infected by *E. necator* in control plots by mid-July. Surprisingly, metrafenone did not prevent disease development on grape clusters, which resulted similar to control (0.5% and 15.75% protection index for disease incidence and severity, respectively), and only partially protected leaves (32.3% and 64.5% protection index for disease incidence and severity, respectively).

In 2011 and 2012, metrafenone treatment reduced significantly the disease incidence and severity on leaves and grape clusters compared to control. On the contrary, metrafenone treatment did not reduce significantly the disease incidence and severity in 2013, which were similar to control (data not shown).

### 3.3 Identification of metrafenone-resistant strains in laboratory

Due to the surprisingly low efficacy of metrafenone observed in the Timoline field in 2013, infected leaves and grape clusters were collected from the experimental vineyard and ten monoconidial isolates of *E. necator* were obtained (Table 1). Three additional monoconidial samples were isolated from a commercial vineyard in the Franciacorta area. We previously determined that the sensitivity of strains collected before 2013 to metrafenone in terms of mycelium growth and sporulation was lower than  $12.5 \text{ mg L}^{-1}$ , concentration that inhibited the mycelium growth by 95% and completely inhibited sporulation (data not shown).

To assess the sensitivity of the 13 putatively resistant strains collected in 2013, mycelium growth and sporulation of strains grown on plants treated with metrafenone at the concentration used in field ( $125 \text{ mg L}^{-1}$ ) and 10-times higher ( $1250 \text{ mg L}^{-1}$ ) were compared to untreated control. All isolates grew abundantly on control plants; after 14 days of growth their average colony area was  $89.4 \text{ mm}^2$  (standard deviation, SD 39.9) and they produced on average  $2212.1 \text{ spores/cm}^2$  (SD. 1668.8). Two out of 13 strains were metrafenone-sensitive (2C and 3C), and did not grow on metrafenone-treated plants (Table 2 and Table 3). Four strains (1M, 3M, 4M and 3F) grew and sporulated equally to control at both metrafenone concentrations. The remaining tested strains also grew and sporulated on metrafenone-treated plants, but to a lower extent than on control plants, especially at the concentration of  $1250 \text{ mg L}^{-1}$ .

In 2014, single conidial-chains from sporulating colonies collected directly in field were put to germinate on leaves treated or not with metrafenone. Two out of 10 conidia developed colonies on control leaves, indicating 20% infection rate. In contrast, from 120 conidia transferred on metrafenone-treated ( $125 \text{ mg L}^{-1}$ ) leaves, only two potentially resistant colonies were obtained (8.3% infection rate).

### 3.4 Cross-resistance

The metrafenone-sensitive strain (2C) grew and sporulated abundantly on control plants, while it was efficiently controlled by metrafenone and the other tested fungicides. On the contrary, the two resistant strains (1M and 2M) grew abundantly on control and metrafenone-treated plants, with 100% of leaf surface covered by sporulating colonies (Figure 3A and B). Complete colonization of leaf surface was also observed for pyriofenone-treated plants, which confirmed our expectations of cross-resistance between metrafenone and pyriofenone (Figure 3C). However, the growth of metrafenone-resistant strains was fully controlled by the other two fungicides representatives of QoI and DMI groups (azoxystrobin and myclobutanil, respectively), which indicates absence of cross-resistance with these groups (Figure 3D and E).

## 4 DISCUSSION

Powdery mildew is one of the major diseases of grapevine worldwide. Although cultural practices and biological control help reducing the severity of epidemics, its management relies on the use of fungicides.<sup>1</sup> However, resistant strains of *Erysiphe necator* to several major fungicide classes were described, including QoIs and DMIs.<sup>10,12,13</sup> QoIs are typical fungicides with single-site mode of action, and the resistance often leads to suboptimal control or complete loss of activity in field.<sup>14,18</sup> On the contrary, the resistance to DMIs is thought to be oligogenic and quantitative, and the resistance levels in field are often low and only rarely result in control failure.<sup>30</sup> Moreover, the use of synthetic pesticides is becoming severely limited due to the new European Union strategy, which heavily restricts the registration and use of chemicals and favors alternative methods.<sup>31,32</sup> In this situation, reduced efficacy of a fungicide to control the powdery mildew epidemics represents a serious problem

as it may imply resistance in the pathogen population, which could ultimately lead to loss of efficacy of the entire fungicide group.

Metrafenone was registered in Europe in 2006 to manage powdery mildews and eye spot disease (*Oculimacula* spp.) epidemics in cereals and since then it has been used extensively especially on cereals, cucurbits and grapevine. The first report of resistance to metrafenone in *Blumeria graminis* f. sp. *tritici* appeared in the literature only after three years of its use, and 3.9% of tested isolates were classified as moderately or highly resistant, while no resistance was observed in *B. graminis* f. sp. *hordei*.<sup>21</sup>

In our study we investigated the sensitivity of *E. necator* to metrafenone in the Franciacorta area in northern Italy. We demonstrated the reduced efficacy of metrafenone to control grapevine powdery mildew in field in 2013, as there were no differences observed in disease incidence and severity between the untreated control and the metrafenone-treated plots. Based on this evidence, 13 putatively resistant samples were collected in 2013 from the experimental vineyard and an additional commercial vineyard in the Franciacorta area, to determine their response to metrafenone in laboratory. Metrafenone does not inhibit the germination of *E. necator* spores, but blocks further development beyond the formation of appressoria (data not shown),<sup>20</sup> therefore, its activity was assessed in terms of pathogen mycelium growth and sporulation. Examples from other fungicide-resistant pathogens indicate that strains with lower resistance factors are still well controlled by the recommended field doses of the fungicides,<sup>10,33,34</sup> however, 85% of the strains obtained in this study showed moderate to high resistance to metrafenone, with the estimated resistance factor higher than 100. In fact, all resistant strains grew and sporulated also at 1250 mg L<sup>-1</sup> metrafenone, a concentration 10-times higher than the recommended field dose. The detection of two additional resistant isolates in 2014, even after metrafenone treatments were discontinued, indicates that metrafenone-resistant strains persisted in the experimental

vineyard also in the absence of selection. We hypothesize that the low frequency of their recovery might have been caused by a fitness penalty in comparison to metrafenone-sensitive strains, or due to influx of sensitive isolates from surrounding vineyards.

The cross-resistance studies indicate that metrafenone-resistant strains are still controlled by fungicides representative of two groups widely used in powdery mildew management: strobilurins (azoxystrobin) and DMIs (myclobutanil). However, our data indicate cross-resistance with pyriofenone, a new fungicide belonging to the U8 FRAC group as metrafenone.<sup>35</sup> These results further confirm that the two fungicides most likely act in the same molecular pathway, hypothesized to be involved in actin localization or hyphal morphogenesis.<sup>19</sup>

In contrast to QoIs or DMIs, where mutations causing the resistance are known, the monitoring for metrafenone-resistant strains remains difficult, as no quick PCR-based methods are available.<sup>14,18,36</sup> It has been hypothesized that metrafenone compromises hyphal tip organization via the disruption of signal transduction, involving Rho or Ras GTP-ases.<sup>17,19</sup>

Our identification of metrafenone-resistant strains provides a valuable tool for studying possible mechanism of action, also by transcriptome analysis and using specific microsatellite markers.<sup>37,38</sup>

To our knowledge, this is the first paper that reports loss of metrafenone efficacy in field due to resistance in *E. necator*. Previously, one *E. necator* metrafenone-resistant strain was detected in a monitoring study in 2010, however, resistance of this strain decreased rapidly after several transfers indicating that adaptation was not stable or that the strain was a mix of sensitive and adapted isolates, and that the sensitive isolates dominated the population more and more during propagation steps in the following year.<sup>39</sup> Further studies are needed to understand the implications for metrafenone use in the IPM programs. Reduced fitness has been observed in fungicide-resistant strains of some pathogens,<sup>40,41</sup> however, in most cases

mutations conferring the fungicide resistance do not cause any obvious fitness penalty.<sup>42,43</sup>

The study on the fitness of metrafenone-resistant strains will be indicative of possible reevaluation and decisions about the use of metrafenone in grape-growing areas. *E. necator* populations can vary from clonal to highly genetically diverse and randomly mating.<sup>44-46</sup> Populations with mixed mating (sexual and asexual), high genetic flow, large effective population size, and high mutation rates have higher potential for breaking down the resistance.<sup>47</sup> The analysis of *E. necator* population structure and genetic diversity of resistant strains could highlight the association of certain haplotypes with resistance traits, and contribute to understand, if the resistant strains have the potential to spread in the pathogen population.

#### **ACKNOWLEDGEMENTS**

The authors would like to thank Dr. Erica Debenedetti for her help with laboratory based experiments.

## 5 REFERENCES

- 1 Gadoury DM, Cadle-Davidson L, Wilcox WF, Dry IB, Seem RC, Milgroom MG. Grapevine powdery mildew (*Erysiphe necator*): a fascinating system for the study of the biology, ecology and epidemiology of an obligate biotroph. *Mol Plant Pathol* 2012; **13**: 1–16.
- 2 Glawe DA. The powdery mildews: a review of the world's most familiar (yet poorly known) plant pathogens. *Annu Rev Phytopathol* 2008; **46**: 27–51.
- 3 Reuveni M. Activity of trifloxystrobin against powdery and downy mildew diseases of grapevines. *Can J plant Pathol* 2001; **23**: 52–59.
- 4 Fernandez-Cornejo J. Environmental and economic consequences of technology adoption: IPM in viticulture. *Agric Econ* 1998; **18**: 145–155.
- 5 Caffi T, Rossi V, Legler SE, Bugiani R. A mechanistic model simulating ascospore infections by *Erysiphe necator*, the powdery mildew fungus of grapevine. *Plant Pathol* 2011; **60**: 522–531.
- 6 FRAC. FRAC Code List 2014: Fungicides sorted by mode of action (including FRAC code numbering). 2014; : Online document available at <http://www.frac.info>.
- 7 FRAC. FRAC Pathogen risk list. 2014; : Online document available at <http://www.frac.info>.
- 8 Pearson RC. Benomyl-resistant strains of *Uncinula necator* on grapes. *Plant Dis* 1980; **64**: 677.
- 9 Garibaldi A, Gullino ML, I. M. Comparsa in Italia di una popolazione di *Uncinula Necatrix* (SCHW.) Burr. che presenta ridotta sensibilità verso alcuni inibitori della biosintesi degli steroli. In: *Giornate fitopatologiche: Protezione delle piante, Qualita, Ambiente 1990*. 1990, pp 143–150.
- 10 Délye C, Laigret F, Corio-Costet MF. A mutation in the 14 alpha-demethylase gene of *Uncinula necator* that correlates with resistance to a sterol biosynthesis inhibitor. *Appl Environ Microbiol* 1997; **63**: 2966–70.
- 11 Genet J-L, Jaworska G. Baseline sensitivity to proquinazid in *Blumeria graminis* f. sp. *tritici* and *Erysiphe necator* and cross-resistance with other fungicides. *Pest Manag Sci* 2009; **65**: 878–84.
- 12 Wilcox W, Burr J, Riegel D, Wong F. Practical resistance to QoI fungicides in New York populations of *Uncinula necator* associated with quantitative shifts in pathogen sensitivities. *Phytopathology* 2003; **93**: S90.
- 13 Green EA, Gustafson GD. Sensitivity of *Uncinula necator* to quinoxifen: evaluation of isolates selected using a discriminatory dose screen. *Pest Manag Sci* 2006; **62**: 492–7.

- 14 Miles LA, Miles TD, Kirk WW, Schilder AMC. Strobilurin (QoI) resistance in populations of *Erysiphe necator* on grapes in Michigan. *Plant Dis* 2012; **96**: 1621–1628.
- 15 Frenkel O, Cadle-Davidson L, Wilcox WF, Milgroom MG. Mechanisms of resistance to an azole fungicide in the grapevine powdery mildew fungus, *Erysiphe necator*. *Phytopathology* 2015; **105**: 370–377.
- 16 Leroux P, Walker A-S. Multiple mechanisms account for resistance to sterol 14 $\alpha$ -demethylation inhibitors in field isolates of *Mycosphaerella graminicola*. *Pest Manag Sci* 2011; **67**: 44–59.
- 17 Hollomon DW. New modes of action contribute to resistance management. In: Thind TS (ed). *Fungicide resistance in crop protection: risk and management*. CABI, 2011, pp 104–115.
- 18 Brent KJ, Hollomon DW. *Fungicide resistance in crop pathogens: How can it be managed?* Fungicide Resistance Action Committee (Croplife International): Brussels, Belgium, 2007.
- 19 Opalski KS, Tresch S, Kogel K-H, Grossmann K, Köhle H, Hüchelhoven R. Metrafenone: studies on the mode of action of a novel cereal powdery mildew fungicide. *Pest Manag Sci* 2006; **62**: 393–401.
- 20 Schmitt MR, Carzaniga R, Cotter HVT, O’Connell R, Hollomon D. Microscopy reveals disease control through novel effects on fungal development: a case study with an early-generation benzophenone fungicide. *Pest Manag Sci* 2006; **62**: 383–92.
- 21 Felsenstein F, Semar M, Stammler G. Sensitivity of wheat powdery mildew (*Blumeria graminis* f.sp. *tritici*) towards metrafenone. *Gesunde Pflanz* 2010; **62**: 29–33.
- 22 Cortesi P, Bisiach M, Ricciolini M, Gadoury DM. Cleistothecia of *Uncinula necator* - An additional source of inoculum in Italian vineyards. *Plant Dis* 1997; **81**: 922–926.
- 23 Townsend G, Heuberger J. Methods for estimating losses caused by diseases in fungicide experiments. *Plant Dis Report* 1943; **27**: 340–343.
- 24 Abbott WS. A Method of computing the effectiveness of an insecticide. *J Econ Entomol* 1925; **18**: 265–267.
- 25 Cortesi P, Ottaviani MP, Milgroom MG. Spatial and genetic analysis of a flag shoot subpopulation of *Erysiphe necator* in Italy. *Phytopathology* 2004; **94**: 544–550.
- 26 Rasband W. ImageJ 1997-2012. U. S. Natl. Institutes Heal. Bethesda, Maryland, USA. 2012.<http://imagej.nih.gov/ij/>.
- 27 Schneider CA, Rasband WS, Eliceiri KW. NIH Image to ImageJ: 25 years of image analysis. *Nat Methods* 2012; **9**: 671–675.

- 28 R\_Core\_Team. *R: A language and environment for statistical computing*. The R Foundation for Statistical Computing: R Foundation for Statistical Computing, Vienna, Austria, 2013.
- 29 Faria JC, Jelihovschi EG, Allaman IB. *Conventional Tukey Test*. Universidade Estadual de Santa Cruz - UESC, Ilheus, Bahia, Brasil, 2014.
- 30 Cools HJ, Hawkins NJ, Fraaije BA. Constraints on the evolution of azole resistance in plant pathogenic fungi. *Plant Pathol* 2013; **62**: 36–42.
- 31 Steel CC, Blackman JW, Schmidtke LM. Grapevine bunch rots: impacts on wine composition, quality, and potential procedures for the removal of wine faults. *J Agric Food Chem* 2013; **61**: 5189–206.
- 32 Jess S, Kildea S, Moody A, Rennick G, Murchie AK, Cooke LR. European Union policy on pesticides: implications for agriculture in Ireland. *Pest Manag Sci* 2014; **70**: 1646–54.
- 33 FRAC. Mutations associated with QoI-resistance. 2006; : Online document available at <http://www.frac.info>.
- 34 Kunova A, Pizzatti C, Bonaldi M, Cortesi P. Sensitivity of nonexposed and exposed populations of *Magnaporthe oryzae* from rice to tricyclazole and azoxystrobin. *Plant Dis* 2014; **98**: 512–518.
- 35 Ogawa M, Nieto J, Ruggiero P. Pyriofenone: nuovo fungicida antioidico per la difesa della vite. In: *Atti Giornate Fitopatologiche Giornate Fitopatologiche*. 2012, pp 201–206.
- 36 Dufour MC, Fontaine S, Montarry J, Corio-Costet MF. Assessment of fungicide resistance and pathogen diversity in *Erysiphe necator* using quantitative real-time PCR assays. *Pest Manag Sci* 2011; **67**: 60–69.
- 37 Wakefield L, Gadoury DM, Seem RC, Milgroom MG, Sun Q, Cadle-Davidson L. Differential gene expression during conidiation in the grape powdery mildew pathogen, *Erysiphe necator*. *Phytopathology* 2011; **101**: 839–46.
- 38 Frenkel O, Portillo I, Brewer MT, Péros JP, Cadle-Davidson L, Milgroom MG. Development of microsatellite markers from the transcriptome of *Erysiphe necator* for analysing population structure in North America and Europe. *Plant Pathol* 2012; **61**: 106–119.
- 39 Stammler G, Semar M, Strobel D, Dehne HW, Deising B, Fraaije U *et al*. Resistance management of metrafenone in powdery mildews. In: *Modern fungicides and antifungal compounds VII. Proceedings of the 17th International Reinhardsbrunn Symposium, April 21-25 2013, Friedrichroda, Germany*. Deutsche Phytomedizinische Gesellschaft e.V. Verlag, 2014, pp 179–184.

- 40 Karaoglanidis GS, Thanassouloupoulos CC, Ioannidis PM. Fitness of *Cercospora beticola* field isolates – resistant and – sensitive to demethylation inhibitor fungicides. *Eur J Plant Pathol*; **107**: 337–347.
- 41 Saito S, Cadle-Davidson L, Wilcox WF. Selection, fitness, and control of grape isolates of *Botrytis cinerea* variably sensitive to fenhexamid. *Plant Dis* 2014; **98**: 233–240.
- 42 Rallos LEE, Johnson NG, Schmale DG, Prussin AJ, Baudoin AB. Fitness of *Erysiphe necator* with G143A-based resistance to quinone outside inhibitors. *Plant Dis* 2014; **98**: 1494–1502.
- 43 Petit A-N, Vaillant-Gaveau N, Walker A-S, Leroux P, Baillieul F, Panon M-L *et al.* Effects of fudioxonil on *Botrytis cinerea* and on grapevine defence response. *Phytopathol Mediterr* 2011; **50**: 130–138.
- 44 Cortesi P, Mazzoleni A, Pizzatti C, Milgroom MG. Genetic similarity of flag shoot and ascospore subpopulations of *Erysiphe necator* in Italy. *Appl Environ Microbiol* 2005; **71**: 7788–7791.
- 45 Brewer MT, Cadle-Davidson L, Cortesi P, Spanu PD, Milgroom MG. Identification and structure of the mating-type locus and development of PCR-based markers for mating type in powdery mildew fungi. *Fungal Genet Biol* 2011; **48**: 704–13.
- 46 Cortesi P, Pizzatti C, Bertocchi D, Milgroom MG. Persistence and spatial autocorrelation of clones of *Erysiphe necator* overwintering as mycelium in dormant buds in an isolated vineyard in northern Italy. *Phytopathology* 2008; **98**: 148–152.
- 47 McDonald BA, Linde C. Pathogen population genetics, evolutionary potential, and durable resistance. *Annu Rev Phytopathol* 2002; **40**: 349–79.

## FIGURE LEGENDS

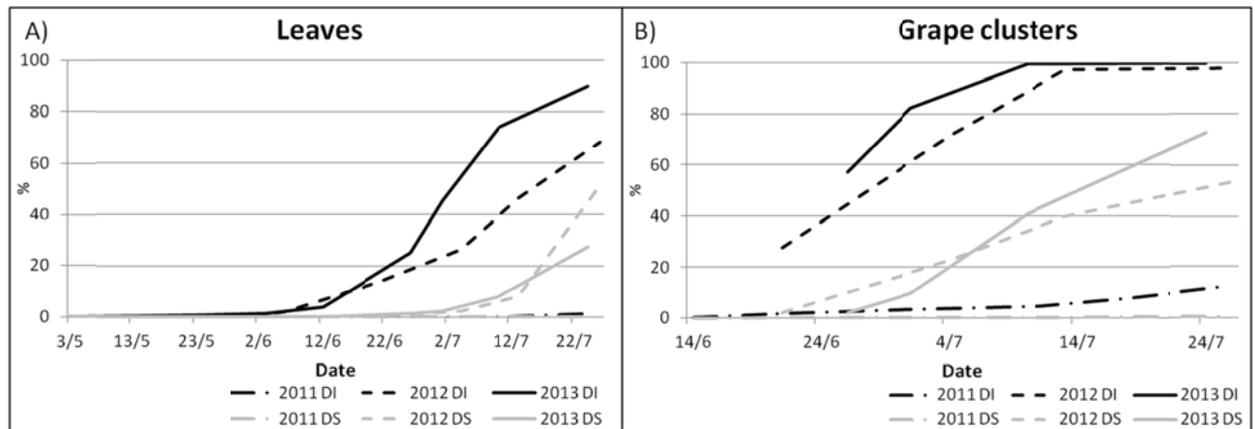


Figure 1: Epidemics of *Erysiphe necator* during 2011-2013 in Timoline (BS), Italy. The dynamics of disease incidence (DI, black) and disease severity (DS, gray) on leaves (A) and grape clusters (B) were recorded each year from the beginning of May to mid-July.

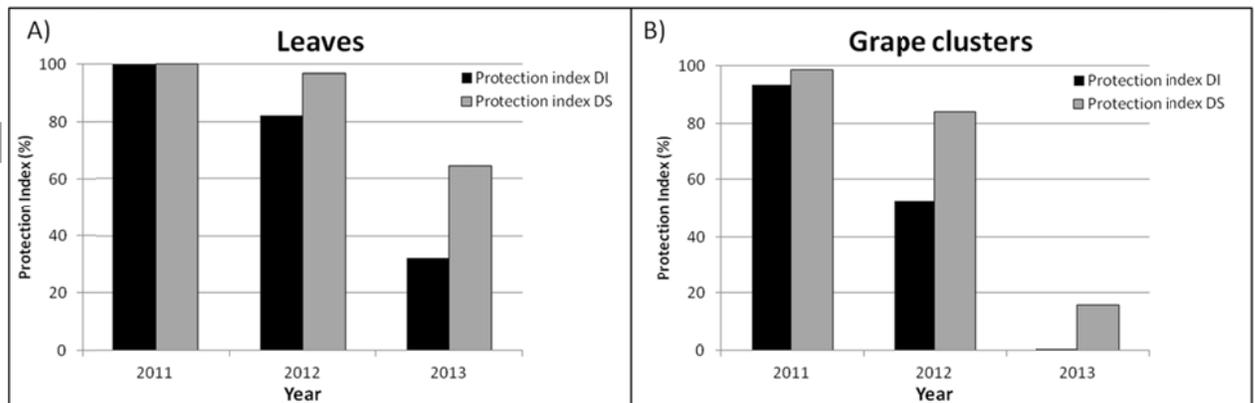


Figure 2: Metrafenone protection indices for disease incidence (DI, black) and disease severity (DS, grey) on leaves (A) and grape clusters (B) in mid-July, in years 2011-2013 in Timoline (BS), Italy.

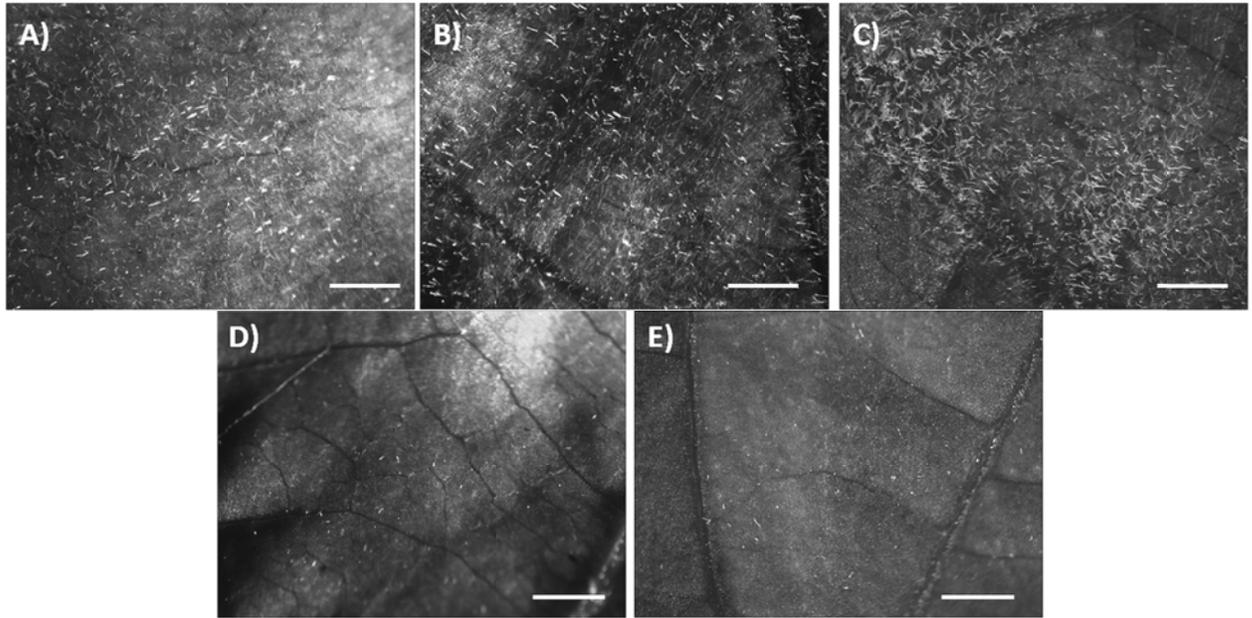


Figure 3: Cross-resistance: *E. necator* metrafenone-resistant strain 1M sporulating on leaves treated with water (A), metrafenone (B) and pyriofenone (C); and inhibition of growth of *E. necator* 1M on leaves treated with azoxystrobin (D) and myclobutanil (E). Leaves were observed at the dissecting microscope at the magnification 20x. The bar represents 1 mm.

## TABLES

Table 1: *Erysiphe necator* strains collected from experimental vineyard in Timoline from control or metrafenone-treated plots, and from commercial vineyards in Franciacorta area in 2013.

<b>Strain</b>	<b>Locality</b>	<b>Treatment</b>	<b>Organ infected</b>
1C	Timoline	Control	Leaves
2C	Timoline	Control	Leaves
3C	Timoline	Control	Grape clusters
4C	Timoline	Control	Grape clusters
1M	Timoline	Metrafenone	Grape clusters
2M	Timoline	Metrafenone	Leaves
3M	Timoline	Metrafenone	Grape clusters
4M	Timoline	Metrafenone	Grape clusters
5M	Timoline	Metrafenone	Leaves
6M	Timoline	Metrafenone	Leaves
1F	Franciacorta	unknown	Grape clusters
2F	Franciacorta	unknown	Leaves
3F	Franciacorta	unknown	Grape clusters

Table 2: Mycelium growth of *Erysiphe necator* strains on control and metrafenone-treated plants.

Strain	Mycelium growth (mm <sup>2</sup> )		
	Control	Metrafenone	
		125 mg L <sup>-1</sup>	1250 mg L <sup>-1</sup>
1C	87.04 (38.65) <sup>1</sup> ns <sup>2</sup>	93.98 (26.02) ns	72.05 (33.98) ns
2C	69.13 (19.57) a	0 (0) b	0 (0) b
3C	42.64 (16.6) a	0 (0) b	0 (0) b
4C	67.01 (17.68) ns	76.92 (23.60) ns	69.4 (13.22) ns
1M	72.88 (31.79) ns	73.15 (21.81) ns	57.58 (15.83) ns
2M	111.11 (40.55) a	110.63 (38.89) a	72.95 (16.95) b
3M	99.93 (26.55) ns	109.83 (42.89) ns	97.57 (28.34) ns
4M	80.24 (12.74) ns	76.03 (4.99) ns	76.8 (19.47) ns
5M	79.12 (35.59) b	117.31 (14.13) a	97.03 (8.77) ab
6M	154.62 (59.36) a	140.03 (26.61) ab	98.85 (22.91) b
1F	84.52 (33.77) a	43.91 (12.18) b	32.4 (6.73) b
2F	90.05 (33.8) a	52.98 (21.78) b	54.27 (19.97) b
3F	107.88 (42.62) ns	101.06 (35.75) ns	82.74 (17.49) ns

<sup>1</sup>The mean value followed by SD; <sup>2</sup>Tukey post hoc test; means in a row with the same letters are not significantly different ( $P = 0.05$ ); ns = not significant.

Table 3: Sporulation of *Erysiphe necator* strains on control and metrafenone-treated plants.

Strain	Sporulation (conidia cm <sup>-2</sup> )		
	Control	Metrafenone	
		125 mg L <sup>-1</sup>	1250 mg L <sup>-1</sup>
1C	2694.05 (1341.83) <sup>1</sup> a <sup>2</sup>	1954.94 (1215) a	758.64 (66.05) b
2C	5112.21 (1622.79) a	0 (0) b	0 (0) b
3C	1227.32 (839.33) a	0 (0) b	0 (0) b
4C	3736.81 (2374.32) a	2677.56 (1864.2) ab	1106.15 (336.59) b
1M	1687.92 (1303.42) ns	1346.67 (1059.37) ns	1236.17 (1057.67) ns
2M	2696.87 (1303.33) a	2992.07 (1507.14) a	931.78 (735.28) b
3M	1460.06 (1029.66) ns	1966.89 (1325.06) ns	2773.22 (2529.84) ns
4M	1523.18 (497.11) ns	1272.06 (468.82) ns	1039.67 (721.71) ns
5M	1325.15 (1436.85) a	2416.44 (726.21) ab	973.17 (429.13) b
6M	2725.8 (1070.9) ns	3488.3 (1337.86) ns	2337.69 (1129.79) ns
1F	1465.04 (1105.83) a	375.95 (210.03) b	239.25 (302.26) b
2F	1357.28 (1287.46) ns	683.75 8 (583.86) ns	940.36 (1014.41) ns
3F	960.11 (563.63) ns	517.3 (264.18) ns	778.37 (543.71) ns

<sup>1</sup>The mean value followed by SD; <sup>2</sup>Tukey post hoc test; means in a row with the same letters are not significantly different ( $P = 0.05$ ); ns = not significant.