

Research Note

Cooperation and Compensation to Mitigate Fungicide Resistance

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Abstract: We evaluated grapegrowers' awareness of fungicide resistance and willingness to adjust fungicide use practices to mitigate this problem in vineyards. We conducted a pilot study surveying a small group of grapegrowers in the United States to assess their knowledge about fungicide resistance and willingness to adjust fungicide use based on the effect that use had on their own farm and their neighboring farms' profits. We found that though growers are generally willing to adjust their fungicide use practices if assisted with the mitigation of resistance, they were less willing to do so when that adjustment would negatively affect their profits. We also evaluated their willingness to adjust their fungicide use when lost profits were remediated with compensation. To understand the relationship between their willingness to change their practices with compensation and their baseline willingness to do so (without compensation), we conducted a logistic regression. Given the small sample inference, we used bootstrapped estimates and observed an increase on growers' willingness to adjust their fungicide use when compensation was available. Our analysis underscores the importance of monetary compensation as an incentive to fight against fungicide resistance.

Key words: cooperation, disease management, FRAC, grape powdery mildew, grower perceptions

Management of the fungal disease grape powdery mildew (GPM; fungal species *Erysiphe necator*) is expensive for grapegrowers (Sambucci et al. 2019). GPM is also a primary cause for loss of grape quality and yield worldwide. Most of the management of this disease focuses on the use of fungicides (Fuller et al. 2014). However, the increase in fungicide resistance in GPM creates a challenge for maintaining disease control (examples: Gubler et al. 1996, Ypema et al. 1997, Wong and Wilcox 2002, Miller and Gubler 2004, Miles et al. 2012, Ouimette 2012, Yamagata et al. 2016).

The risk of fungicide resistance increases when fungicides with the same mode of action are repeatedly applied (Brent and Hollomon 2007). This is exacerbated with the co-occurrence of other conditions that favor resistance selection, such as inappropriate applications (below labeled rates), incomplete spray coverage, and application of fungicides to already-infected plant tissue (Brent and Hollomon 2007). These occur as a part of on-farm choices and application approaches. Thus, factors that drive these decisions are important to consider to reduce the likelihood of fungicide resistance on a commercially relevant scale.

A recent survey of the United States grape industry (252 members) showed that 55% of the respondents consider fungicide resistance to be a moderate to severe problem; the survey also showed that most respondents possessed knowledge of resistance management practices (Oliver et al. 2021). However, knowledge of a practice may not mean that the practice is applied. For example, Lybbert et al. (2016) found evidence that, despite knowledge of GPM risk (through the use of formal risk indices), growers kept their usual spray timing without reducing the number of sprays. Ultimately, Lybbert et al. (2016) found that growers engaged in complex, multidimensional responses to risk information, and those decisions resulted in a net negative environmental impact in this study. Their findings point to a need for a comprehensive examination of grower behavior in response to information, as access to information does not necessarily result in anticipated changes in action.

Disease management often focuses on on-farm choices, but some diseases affect broader areas within a region. This is especially important given the aerial dispersion of GPM

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(Falacy et al. 2007). Regional cooperation in disseminating information about how to manage the invasive European grapevine moth in California were valuable in creating a network of growers who then practiced those management approaches (Cooper et al. 2014). Understanding the reasons for an individual's choice of fungicide use, particularly if presented with information on how the choices might affect their own farm or their neighbor's farm, may help with the development of educational approaches and prevention of widespread regional losses in disease control.

This study evaluates grapegrowers' perceptions of fungicide resistance and how that perception may change when considering how neighbor's choices affect each other. The basic assumption in this study is that actions are primarily financially driven, i.e., that the catalyst for an individual to change a current practice is associated with a financial incentive or to avoid a cost. We assumed that for a management approach to expand to a regional activity, cooperation to mitigate fungicide resistance would come from two actions: (i) an individual's general interest in reducing at-risk fungicide use without compensation, and/or (ii) enticement of compensation to reduce the use of at-risk fungicides for their own benefit or for the benefit of their neighboring farms. This study aimed to identify grapegrowers' willingness to cooperate based on fungicide use decisions and the relationship between that willingness and compensation of profit loss.

Materials and Methods

We used a similar survey strategy to that of Llewellyn et al. (2002), who developed hypothetical scenarios in their surveys for participants to consider. Our survey included different scenarios relating to choices of fungicide use, potentially corresponding compensation for the adoption of those choices, and how fungicide use may influence fungicide resistance on the participant's or their neighbor's farm.

The survey had 64 questions (see Supplemental Information) that were distributed among grapegrowers in the United States between October and December 2019 using Qualtrics XM Online Survey Software (Qualtrics.com, LLC). The survey was distributed using viticulture university extension networks across the United States, using their regional Extension email listservs, by publicizing the survey and providing QR code links during regional grapegrower meetings, and through individual direct emails from extension specialists to regional grower groups and representative co-ops. The survey was also posted on the Fungicide Resistance Assessment, Mitigation, and Extension (FRAME) project website (framenetworks.wsu.edu), Twitter, and Facebook pages, where it was reshared by extension specialists to their networks of growers, crop consultants, and other industry members.

The survey was composed of three sections: (i) identification of fungicide use practices, (ii) growers' willingness to cooperate, and (iii) demographics. To identify practices in section (i), we asked questions to gauge growers' current fungicide use practices, such as overall understanding of fungicide resistance and management philosophies. In this study, we defined fungicide use practices as those that

influenced the timing of fungicide application and the rotational choices between different fungicide classes (i.e., Fungicide Resistance Action Committee [FRAC] groups, www.frac.org). We also asked questions about their knowledge of their neighbors' use of fungicide. To identify cooperation in section (ii), we developed questions to directly assess growers' willingness to adjust fungicide practices to mitigate fungicide resistance. This was done through variations of a central question about whether a grower would change their current practices to mitigate fungicide resistance. The varying scenarios allowed for growers to express whether they would be willing to make this adjustment (cooperate) with or without compensation. The survey also included information on the varying effects that adjustment would have on their profits or on the profits of their neighboring growers. The demographic questions (iii) provided information about age, education, and farming location.

Statistical analyses. We conducted a logistic regression analysis to assess the relationship between a grower's choice to cooperate (adjust practices) with compensation and an index of their own baseline willingness to adjust to mitigate development of fungicide resistance. We controlled for a grower's baseline willingness to adjust fungicide use practices in resistance mitigation efforts and whether they have a neighbor grower. The specific model we used was:

$$C_i = \beta_0 + \beta_1 X_i + \beta_2 N_i + e_i$$

where C_i is a binary variable indicating whether grower i is willing to adopt fungicide mitigation efforts if they are compensated ($C_i = 1$ if grower i responded "Yes" and $C_i = 0$ if grower i responded "No" or "Unsure" to survey question 37, Supplemental Information).

The variable X_i is an index indicating grower i 's baseline willingness to adjust fungicide use practices. We defined baseline as willingness to adjust without compensation. The index is composed of the survey questions 26 to 30 and 32 to 35 (Supplemental Information). These questions were related to each grower's willingness to adjust some aspect (general practice, frequency, timing, or FRAC groups used) when presented with alternate scenarios (either related to consequences of their compliance or preexisting circumstances). It should be noted that the questions used in the index did not contain implicit or explicit compensation (unlike question 37, Supplemental Information) for their cooperation in reducing fungicide resistance. Therefore, a higher value for this index represents a general willingness to alter fungicide use practices without monetary compensation to mitigate fungicide resistance development.

The final variable, N_i , specifies whether grower i indicated they have a neighboring grower (question 12, where $N_i = 1$ if grower i responded "Yes" and $N_i = 0$ if grower i responded "No"). The last term is an error term, which is assumed to be independently and identically distributed. The central reason that the logistic regression is used is because the dependent variable, C_i , is a binary variable. Choosing logistic regression rather than probit (the main alternative when the dependent

variable is categorical) is predominately dictated by preference for interpretation.

Our sample size was small ($n = 38$; not all surveys were complete), and because asymptotic inference is often unreliable in small samples, we bootstrapped parameter estimates and standard errors in R (Robert and Casella 2004). A random sample was obtained with replacement from our original data set equal to the number of observations to form a new sample. We stored the corresponding parameter estimates associated with this new random sample and the model presented above. This process was repeated 1000 times; therefore, 1000 new randomly sampled data sets and corresponding sets of parameter estimates were obtained. From these, the mean of the parameter estimates and standard errors were calculated and used to compute confidence intervals and p values.

Results

Demographics. The survey was accessed by 57 growers, but not all completed all questions in the survey. Any presented statistical representation (i.e., percent of respondents) is related to the number of actual responses for that question. Growers mainly resided in Washington State (47.4%, $n = 18$), followed by Georgia (18.42%, $n = 7$) and Oregon (15.8%, $n = 6$). These demographic data are summarized in Supplemental Table 1. Pacific states (California, Washington, Oregon) represent 98% of all grape acreage in the country, but no responses were received from California. While the survey was shared extensively with California growers through the avenues previously described, there were multiple viticulture-related surveys being distributed at that time, which likely resulted in survey fatigue of this heavily-targeted audience. Additional demographic data are presented in Supplemental Table 1.

Important factors for designing a fungicide program. Growers were mainly concerned about quality (51.3%) and price (18.0%) of a fungicide brand ($n = 39$). Respondents did not report a strong brand loyalty; only 2.0% had never changed fungicide brands. Approximately 40% of respondents indicated that they change fungicide brands more than half of the time; of these, 17.1% indicated they changed brands about half of the time, 7.3% changed brands most of the time, and 17.1% always changed brands.

Management philosophies and fungicide program design. The primary management philosophy practiced by respondents was conventional management (42.1%, $n = 24$), which permits the use of all crop-labeled fungicides. However, more than half of the surveyed growers (57.9%) adhered to a non-conventional management philosophy, including certified organic, biodynamic, or sustainable (23.34%); intended (but not certified) organic/biodynamic/sustainable (31.67%); and others (2.89%).

In the survey, we asked whether growers applied fungicides preventatively or curatively. About 70% ($n = 28$) indicated that they apply fungicides both preventively and curatively, whereas 27.5% said they apply only preventively and 2.5% reported applying only curatively. In general, growers followed the fungicide's label, with 93% of respondents

stating that they carefully read instructions. The most common resources used by growers for designing spray programs were extension pest management guides (39.7%, $n = 31$), followed by extension specialists or farm advisors (24.4%, $n = 19$) and local crop consultants (20.5%, $n = 16$).

Awareness of fungicide resistance and neighbors' fungicide use practices. About 80.5% ($n = 33$) of respondents indicated that they had at least one neighboring farm, and 87.9% ($n = 33$) claimed that the closest neighboring farm was within 1.6 km. Growers indicated that their neighbors mainly grew winegrapes (48.5%) and apples (24.2%).

Respondents were asked about their knowledge of their neighbor's fungicide use practices (Figure 1). Approximately half of the growers (51.5%, $n = 17$) indicated they know when their neighbor is applying a fungicide most of the time or always. However, 15.2% ($n = 5$) of the respondents indicated they are never aware, and 27.3% indicated that they are sometimes aware.

Respondents were generally aware of the causes and consequences of fungicide resistance (97.6%, $n = 40$). However, 39.0% indicated they have encountered fungicide resistance on their own farm (either through direct detection of a resistant fungus or assumed resistance due to a disease control failure). Among the responding growers, a high degree of uncertainty remained about whether their neighbors' choices affected their own disease control efforts, with 63.6% of respondents stating that they had not considered the effects of their neighbors' fungicide use on their own disease control efforts.

However, knowing what practices one's neighbors are using for both disease management and fungicide resistance mitigation may directly affect the approach of another. Approximately one-third (36.4%) of the growers indicated that they have considered how their neighbor's use of fungicides may affect their own control efficacy (Figure 2), whereas 45.5% indicated that they have not considered how their neighbor's use of fungicides could be impacting their disease control efforts.

Willingness to change practices (cooperate). Among our respondents, 90.5% ($n = 38$) were willing to make changes to their fungicide use practices (e.g., completely stop using fungicides) if they knew fungicide resistance was a problem for that fungicide (Figure 3). When asked if they would be willing to stop using a problematic fungicide if they knew it negatively affected their neighbor, 76.2% ($n = 32$) of respondents were willing to do so. When asked whether they would alternate FRAC groups in their fungicide rotations, 88.1% of respondents were willing to cooperate to help their neighbor. When asked about changing the frequency of their applications, 69.0% of respondents were willing to cooperate, and 26.0% were unsure about changing their frequency of applications to help their neighbor. When growers were not willing to cooperate (no = 7.1%, or unsure = 4.8%), their reasons were: 1) they adhered to a specific production standard (certification) and therefore could not adjust their own program; 2) they were concerned that there were too many other more important variables that ultimately dictate how a

fungicide should be used; 3) they thought their practices associated with drift mitigation of spray meant that there was very little risk of cross-contamination of fungicides, and thus, their fungicide use would not affect their neighbor; or 4) they believed that the fungicides (FRAC groups) they were using were not affected by fungicide resistance development.

To identify their willingness to cooperate (Table 1), defined as adjusting their fungicide use to mitigate development of fungicide resistance when it affects their or their neighbors' profits, growers were generally willing to consider changes as long as their profits were not affected (97.4%). If adjusting fungicide use harmed their profits but could improve management of fungicide resistance, 35.9% of respondents were willing to adjust and 41.0% were unsure. If their adjustments in fungicide use practices improved their profits but hurt their neighbor's profits, more respondents were unsure of whether they would make the change (61.5%).

We also evaluated the respondents' willingness to adjust their fungicide use if there was monetary compensation for profit loss. In the face of their own farm profit loss, 79.5% of the growers indicated they would be willing to adjust their fungicide use to help their neighbor and mitigate fungicide resistance if they were compensated to do so. Among this group, 37.9% were willing to cooperate if they were exactly compensated for their loss in profits, 41.4% would cooperate if they were mostly compensated (75% of lost profits returned), and 20.7% would cooperate if they were partly compensated (25 to 50% of lost profits returned). In this situation, 15.4% of respondents were unsure if they would make an adjustment even if they were compensated for their profit loss.

The estimated coefficient for our baseline willingness-to-adjust index was statistically different from zero (Table 2). This estimate indicates that a one-unit increase in a grower's baseline willingness-to-adjust index (reflecting that a grower responds "Yes" to one of the included questions composing the index) is correlated with a 0.0697 increase in the log-odds of a grower's willingness to adjust fungicide use to mitigate fungicide resistance when offered compensation.

This estimate can be used to determine the range of probabilities that a grower in our study would be willing to adjust fungicide use when offered compensation. The probability that a grower would adjust their use if they were compensated for profit loss ("Yes" on Question 37, Supplemental Information) ranged from ~50 to 65%. The lowest end of the range is the probability associated with a grower who also chose "No" or "Unsure" for all of the questions included in the baseline willingness-to-adjust index. The highest probability is associated with a grower who chose "Yes" for all the included questions. This indicates that the grower has a very high baseline willingness to adjust their fungicide use practices to mitigate the causes and/or consequences of fungicide resistance.



Figure 1 Frequency of grapegrowers' responses to the question on whether they were aware of when their neighbor applied fungicides.

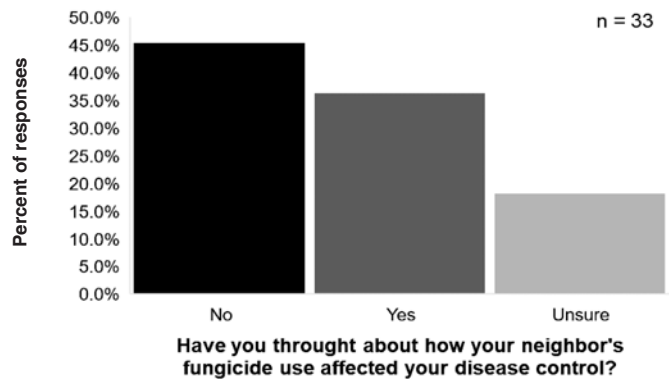


Figure 2 How grapegrowers responded to the question of whether they thought about or noticed if their neighboring farm's fungicide use practices affected their ability to maintain disease control in their own vineyard.

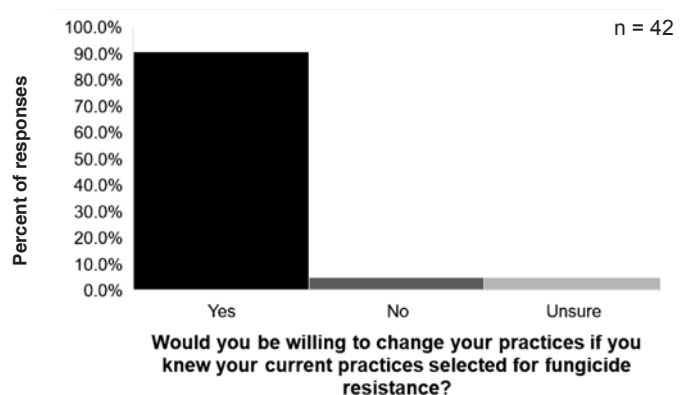


Figure 3 Grapegrowers' willingness to adjust fungicide use practices if they became aware that their practices resulted in selection for fungicide resistance.

Discussion

We assessed grapegrowers' self-reported knowledge of fungicide resistance as well as their current practices of GPM management and willingness to cooperate to mitigate fungicide resistance. Similar to Oliver et al. (2021), we found that the majority of grapegrowers were aware of the causes and consequences of fungicide resistance for their vineyard operation. It is important to highlight that the small size of our sample and the spatial distribution of the growers mainly concentrated in the state of Washington limits the scope of our findings.

Grapegrowers value fairness in regional management decisions. Our results suggest a preference among growers for fairness. A large proportion of respondents were willing to adjust their actions if their own and their neighbor's profits were unaffected or if they both suffer decreases, but the proportion of respondents that were willing to cooperate was greatly reduced when one grower benefits and the other one suffers losses. This behavior has been previously reported in the behavioral economics literature (Fehr and Schmidt 1999).

Compensation is likely needed to truly influence choices. Growers' baseline willingness to adjust fungicide use was positively correlated with their odds of indicating they would be willing to do so for compensation (Table 2). Based on our estimation, if growers indicated that they were willing to cooperate on all questions that compose the index, the probability that they are willing to cooperate with compensation was 65%. This is an increase of 15 percentage points compared with growers who indicated that they were unwilling or uncertain about changing a fungicide use practice. Because growers are willing to cooperate to achieve a common goal, offering compensation may improve the likelihood of cooperation. One potential mode of compensation could be through local, state, or federal policies related to fungicide stewardship and general use. Monetary transfers have been previously examined for the control of mammal population and transboundary species

invasions (Bhat and Huffaker 2007, Liu and Sims 2016). Additional incentives could come through the various third-party vineyard sustainability certification standards that would encourage the use of certain practices. While this would likely not be direct financial compensation, it would potentially be compensation offered in the form of scoring points necessary for recertification that are common with these standards.

Can better educational programs increase willingness to cooperate/adjust fungicide use practices? In our survey, growers were presented with different scenarios in which they could alter one aspect of their fungicide use practice to prevent their neighbors' profits from being negatively affected (in the situation in which fungicide resistance was the cause). Fungicide quality was a primary driver for the choice of fungicide by growers. Hence, more educational language that is focused on how fungicide performance is lost due to fungicide resistance may influence fungicide choice. This focus is different than primarily focusing on disease control failures. Focusing on fungicide quality forces the dual focus on money lost due to use of an ineffective product (product costs) and subsequent crop failures (yield loss). Hands-on learning and practical application are the fundamental keys to adult educational programming (Prell et al. 2009, Franz et al. 2010, Hoffman et al. 2015, Leach et al. 2019) and are critical to the development of successful grower educational networks (Cooper et al. 2014, Hoffman et al. 2015, Oliver et al. 2021). Given that many of our respondents indicated they were generally aware of what their neighbors were spraying (Figure 1) but were not always sure if those sprays may affect their operation (Figure 2), further organization of regional cooperative grower groups focused on mitigation of fungicide resistance may benefit their baseline education and willingness to cooperate.

Finally, the survey provides valuable insights on how monetary compensation can encourage grapegrowers to adjust their use of fungicides to mitigate fungicide resistance, even when their own or their neighbors' profits are affected. We found that different levels of compensation triggered different responses toward cooperation among grapegrowers. This observed strategic behavior is the key to a successful tool that achieves cooperation on use of fungicide designed to mitigate fungicide resistance.

Conclusion

This study examined grapegrowers' willingness to adjust their fungicide use practices when facing fungicide resistance. We developed a survey to explore the possible ways and motivations that growers would be willing to cooperate (adjust a fungicide use practice) to mitigate fungicide resistance. While our sample size was small and limited in regional scope, we found that 35.6% of the respondents were willing to adjust their practices if there was a loss in profit. Respondents were also willing to cooperate (reduction of fungicide use and compensation of neighboring growers) in an effort to solve regional challenges associated with fungicide resistance. Given that our study focused on a small sample of grapegrowers, more research is needed to truly understand the United States grapegrower as a whole.

Table 1 Percent of respondents (n = 39) who indicated they would cooperate if they knew that such cooperation reduces fungicide resistance, considering the effect on their profits and neighbor's profits.

	Increased neighbor profits	Decreased neighbor profits	Did not affect neighbor profits
Increased own profit	-	30.8%	-
Decreased own profit	35.9%	33.3%	-
No effect on own profit	94.87%	-	97.4%

Table 2 Results for the logistic regression analysis.

Model parameters	Estimates ^a	Std. error
Intercept, β_0	0.2063	0.2958
Baseline willingness-to-adjust (cooperate) index, β_1	0.0697*	0.0438
Neighbor, β_2	0.1553	0.1929

^aSignificance: * indicates $p = 0.01$.

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