# Fungicide Resistance and Misinformation: A Game Theoretic Approach*

Chelsea A. Pardini†

Ana Espínola-Arredondo‡

April 15, 2021

**Abstract**

Fungicide resistance developed by pathogens that grapes are susceptible to is problematic for the industry today. We provide further insight into the strategic behavior of grape growers when their choices of fungicide levels generate a negative intertemporal production externality in the form of fungicide resistance. We find that when growers encounter this type of externality, they choose a fungicide level that exacerbates fungicide resistance. We examine a compensation mechanism in which a grower's reduction of fungicide usage is compensated by his neighboring grower. This mechanism is designed to ameliorate fungicide resistance and we show that it induces the socially optimal level; however, misinformation about the severity of the fungicide resistance generates distortions. We show that the information available to growers about fungicide resistance severity is essential for its mitigation with the proposed compensation mechanism. In particular, we find that if the misinformed grower considers fungicide resistance to be severe, then it is preferable that he provides compensation.

*Keywords*: Fungicide resistance, game theory, compensation mechanism, intertemporal externality, misinformation
*JEL Codes*: $C73$, $D21$, $H23$, $Q16$

---

*We gratefully acknowledge financial support from the USDA-NIFA-SCRI program under award number 2018-03375 titled "FRAME: Fungicide Resistance Assessment, Mitigation, and Extension Network for Wine, Table, and Raisin Grapes." We also are very thankful for the advice, suggestions and comments from Félix Muñoz-García, Michelle Moyer, and Shanthi Manian. We are grateful for the comments from the AAEA 2020 Virtual Meeting, AERE-SEA 2020 Virtual Meeting, AERE-EEA 2021 Virtual Meeting, and the Montreal Workshop on Resource and Environmental Economics.

†323E Hulbert Hall, School of Economic Sciences, Washington State University. Pullman, WA 99164.

‡101B Hulbert Hall, School of Economic Sciences, Washington State University. Pullman, WA 99164.

# 1 Introduction

The problem of fungicide resistance in powdery mildew for grape growers is pervasive and well-documented. Grape growers depend upon fungicide-based management for 95 percent of their yields (Gianessi and Reigner, 2006). Fungicide resistance[1] requires increased applications of fungicide for the same level of powdery mildew control,[2] which not only has cost implications for grape growers, but also negative environmental and health consequences.[3] Pimentel (2005) estimates that the costs of pesticide resistance are more than $1.5 billion a year in the United States (US) alone. The challenge of addressing fungicide resistance is in part a collective action problem, since a grower's use of fungicide can exacerbate the fungicide resistance that neighboring growers experience (see, for example (Sexton et al., 2007)); therefore, efforts to mitigate it can benefit from increased understandings of the strategic choices of grape growers in their selection of fungicide levels.

In our paper, we aim to answer the following questions: (i) How do grape growers adjust their fungicide usage when facing fungicide resistance? (ii) Does there exist a compensation mechanism that can help to reduce fungicide resistance? and (iii) How does misinformation about fungicide resistance severity affect the performance of the compensation mechanism? Similar to Regev et al. (1983), Cornes et al. (2001), Ambec and Desquilbet (2012), Martin (2015), and Desquilbet and Herrmann (2016), we address the tension that growers face between needing fungicide in grape production while also facing increased fungicide resistance in future periods as a result of its use. Along with Regev et al. (1983) and Martin (2015), we are mainly concerned with developing a tool that can facilitate the internalization of

[1]There are two broad types of fungicide resistance: quantitative and qualitative. In quantitative resistance, the active ingredient still works; however, a grower needs increasingly more fungicide to achieve the same level of control; that is, resistance is continuous rather than discrete (Corwin and Kliebenstein, 2017). We consider quantitative resistance in this analysis.

[2]Powdery mildew is a prominent pest species for crops including grape and wheat, and resistance development presents a significant problem for growers in, for example, Canada, China, Europe, and the US (see Vielba-Fernández et al. (2020) for additional and specific examples).

[3]For more details see, for example, Christ and Burritt (2013), Sambucci et al. (2019), and Sexton et al. (2007).

fungicide resistance, and negative intertemporal production externalities more generally.

A central contribution of our analysis is the examination of a compensation mechanism to address the problem of fungicide resistance. It belongs to the second of the two policy approaches discussed by Regev et al. (1983); namely, rather than examining a subsidy[4] as in Martin (2015), we study a compensation mechanism that allows growers to voluntarily restrict their fungicide use and receive compensation for their corresponding loss in profits.[5,6] Growers who do not restrict their fungicide use provide the compensation.[7] The compensation mechanism has several advantages, for instance, it does not require mandating fungicide levels unilaterally for all growers in all periods and it promotes cooperation among growers. The compensation mechanism we consider is similar to those proposed by, for example, Bhat and Huffaker (2007), Liu and Sims (2016), and Sims et al. (2018). Bhat and Huffaker (2007) develops a self-enforcing cooperative agreement with variable transfer payments to control, as an example, a mammal population. Liu and Sims (2016) considers using side payment to incentivize producers to coordinate control of transboundary species invasions in a spatial-dynamic control model. Sims et al. (2018) determines the optimal timing of risk-reduction strategies for addressing problems of ecological change, using bioinvasion as an example, and discusses the possibility for compensation to induce coordination. Lemarié and Marcoul (2018), show that pesticide users (e.g., growers) benefit from coordination, where they define coordination as considering the impact of future resistance on their profits, and that certain

[4]A revenue neutral subsidy that induces a socially optimal amount of fungicide usage requires an informed regulator. However, in certain contexts, information can be difficult to collect for the regulator.

[5]In the US, for example, the Environmental Protection Agency (EPA) determines highest admissible levels, or tolerances, of pesticide residue on or in food. In this sense, growers already face some form of quantity restriction on pesticide use.

[6]In a different setting where a bioinvasion occurs in one jurisdiction before moving to neighboring jurisdictions, Sims et al. (2018) study the benefit of delaying mitigation and focus on uncertainty surrounding the risk of bioinvasion in future areas.

[7]See, for example Krishna et al. (2013), who estimate the compensation that farmers are willing to accept in order to change production behavior to increase biodiversity. Also, farmers have demonstrated a willingness to cooperate with each other to address pest resistance (see, for example, Lucchi and Benelli (2018)). Finally, Sangkapitux et al. (2009) show that upstream and downstream stakeholders are willing to cooperate using a compensation scheme in order to implement agricultural practices that are better for the environment.

circumstances incentivize pesticide manufacturers to share information about the likelihood of future resistance with them. Our compensation mechanism allows for growers to decide their input levels, providing them with a flexible tool to mitigate the problem of fungicide resistance.

We begin by examining a two-stage complete-information game between two representative grape growers before ultimately extending to a scenario accounting for misinformation. In the first stage, growers simultaneously choose profit-maximizing input levels of fungicide and all other inputs. In the second stage, growers again must choose input levels, but they also experience the fungicide resistance externality. This negative intertemporal production externality makes it necessary for growers to use more fungicide in stage two to achieve the same level of output in stage one (thus illustrating fungicide resistance).

Similar to Cornes et al. (2001), we consider a discrete-time model. This choice renders our analysis distinct to other such as Cobourn et al. (2019), Liu and Sims (2016), and Martin (2015), who study dynamic settings. Like Ambec and Desquilbet (2012), we limit the central model to two-stages because it allows for sufficient examination of the intertemporal effects of fungicide resistance (while providing analytic solutions from which we can infer grower behavior).

We heed the warning in Finger et al. (2017) to avoid designing a policy considering only a single input in isolation. Therefore, similar to Skevas et al. (2013), we examine a model that provides insights into the effect of the externality on the level of other inputs as well. We limit the technology of our growers to critically depend upon the use of fungicide, unlike others including Regev et al. (1983) and Martin (2015), for a number of reasons. By refraining from considering that growers have access to a backstop technology,[8] we incorporate farmers' documented reticence to reduce pesticide use (see, for example Skevas et al. (2012)). Moreover, our analysis provides additional insight for fungicide resistance mitigation efforts when

[8]Though alternatives exist for powdery mildew control, fungicide-based management continues to be central, especially for grape powdery mildew (for more details, see Oliver and Hewitt (2014)).

constrained growers cannot help but aggravate quantitative fungicide resistance; namely, we emphasize the tension these growers face between needing to apply fungicide and facing the consequences of those usage levels while not having access to alternative technology. Therefore, our paper provides insights that are applicable to growers' associations especially when growers must continue to use a fungicide that contributes to resistance.

Currently, grape growers are not generally equipped with accurate information about fungicide resistance. In fact, the Fungicide Resistance Assessment, Mitigation and Extension (FRAME) Network, as part of their motivation for their efforts, emphasizes that, "There is currently no effective system to monitor or predict fungicide resistance; it is usually identified after a management failure."[9] To address the current scenario, we extend our model to allow for misinformation, where one of the growers incorrectly assesses the severity of fungicide resistance. We examine four separate cases: i) the central two-stage model with fungicide resistance, ii) an extension that incorporates a compensation mechanism designed to lead growers to lower aggregate levels of fungicide, iii) a variation on the first game without compensation where we consider misinformation about the fungicide resistance severity, and iv) an extension of the game where we apply our compensation mechanism in the context of misinformation. By considering a setting in which a grower is misinformed about the severity of fungicide resistance, we evaluate the distortions generated by misinformation. In addition, we provide comparisons between the fungicide levels of these models and the socially optimal level.[10]

We find that the compensation mechanism drives fungicide usage to the socially optimal level, internalizing the intertemporal externality, in the case of complete information. However, the effectiveness of this mechanism becomes less certain when we allow for mis-

[9]For more details see: https://framenetworks.wsu.edu/.While some growers benefit from the expertise of crop consultants and so have marginally better information, due to the absence of an effective system for monitoring and forecasting fungicide resistance, this improved information is limited to certain growers.

[10]We define socially optimal levels as those that maximize the sum of growers' profits. Therefore, socially optimal fungicide levels internalize the intertemporal production externality of fungicide resistance.

information. That is, its performance depends upon the level of misinformation a grower faces about the severity of future fungicide resistance. Our findings suggest that campaigns that help to ameliorate misinformation among growers about the severity of the externality are crucial for its internalization and, thus, the reduction of fungicide resistance. In addition, the development of accessible and effective fungicide resistance tests and forecasts for grape growers could also improve the success of the compensation mechanism by reducing misinformation.

Given that the compensation mechanism requires that a grower restricts their fungicide level while a different grower compensates, misinformation about fungicide resistance severity could be detrimental to its performance. We show that when the grower who provides compensation is misinformed, then it is better (for reducing their fungicide use) if he estimates that future fungicide resistance is more severe than it is in reality.[11] If a growers association could assign certain growers to particular roles in the mechanism, then it would be best if the misinformed grower, who considers fungicide resistance to be more severe than it actually is, provides compensation. Correspondingly, it would be best if the grower who is completely informed restricts fungicide usage and receives compensation.

If growers seek to mitigate the losses to their aggregate profits under misinformation with the compensation mechanism, then it is best if the level of misinformation is low or nonexistent. This underscores the importance of educational efforts about fungicide resistance severity.[12] Our welfare comparisons indicate that, independent of fungicide resistance severity, misinformation exacerbates the difference in welfare between the compensation mechanism and the socially optimal outcome. Hence, it is critical for our proposed mechanism to be implemented in a setting where growers have accurate information about the

[11]This pessimistic behavior has been observed in different contexts, for example, Alpizar et al. (2011) find that farmers in Costa Rica behave more pessimistically when facing uncertainty. Similarly, Menapace et al. (2013) reports pessimistic behavior in agricultural producers.

[12]Goeb et al. (2020) discuss the importance of information for growers to make substitutions away from higher toxicity pesticides.

severity of the intertemporal externality.

The remainder of our paper proceeds as follows. Section 2 describes the central model, corresponding social planner's problem, and the model with the compensation mechanism. Section 3 contains an extension of the game that allows for misinformation and Section 4 concludes.

## 2 Model

We examine the strategic interaction between two grape growers ($i$ and $j$) that must decide the amounts of fungicide, $f_{it}$, and other inputs, $x_{it}$, to maximize their respective profits in period $t$, where $t = 1, 2$. We consider that fungicide usage in the first period results in fungicide resistance that reduces its effectiveness in production in the second period. In this context, aggregate fungicide use generates a negative intertemporal production externality for grower $i$. Specifically, the production functions for grower $i$ in periods 1 and 2, respectively, are

$$q_{i1}(x_{i1}, f_{i1}) \equiv w x_{i1}^{\alpha} f_{i1}^{\beta} \text{ and } \tag{1}$$

$$q_{i2}(x_{i2}, f_{i2}, f_{i1}, f_{j1}) \equiv w x_{i2}^{\alpha} (f_{i2} - \theta[f_{i1} + f_{j1}])^{\beta}, \tag{2}$$

where $w \in [0, \infty)$ is a weather index parameter; a higher value of $w$ indicates that conditions are more favorable to production.[13] We consider that aggregate fungicide levels from the first period $(f_{i1} + f_{j1})$ reduce the effectiveness of fungicide for grower $i$ in the second period. In particular, the productive contribution of each unit of fungicide applied by grower $i$ is diminished by aggregate fungicide levels from period 1. Similar to Martin (2015), the sensi-

[13]The weather index operates as an exogenous multiplier in this analysis and depends on temperature, humidity, sunlight, and other indirect influences.

tivity of fungicide effectiveness in period 2 to aggregate fungicide levels is determined by a fungicide-resistance parameter. We consider this sensitivity parameter to be $\theta \in (0,1)$. If $\theta$ is close to zero, then the fungicide-resistance externality has a negligible impact on production. Conversely, if $\theta$ approaches one then the externality is very severe and its impact on production is high. Finally, $\alpha$ and $\beta$ are the output elasticities of the inputs, where $\alpha, \beta \in (0,1)$. We model fungicide as a yield-increasing input to production and incorporate the tension of fungicide resistance directly within the production function. A damage control framework is used in, for example, Sexton et al. (2007), and earlier Cobb-Douglas specifications in, for example, Carlson (1977), but we deviate from both by considering the problem of resistance in a strategic setting. By doing so, we center the interactions between growers who can aggravate fungicide resistance for each other. The cost function for grower $i$ in period $t$ is

$$C_{it}(x_{it}, f_{it}) \equiv cx_{it} + zf_{it}, \tag{3}$$

where the first term represents the cost of all inputs other than fungicide (with marginal cost $c$) and the second term is the cost of applying fungicide (with marginal cost $z$). We do not impose any condition between $c$ and $z$ (i.e., $c \lesseqgtr z$). Therefore, the profit function for grower $i$ in the first period is

$$\pi_{i1}(x_{i1}, f_{i1}) = pwx_{i1}^{\alpha} f_{i1}^{\beta} - cx_{i1} - zf_{i1}, \tag{4}$$

where prices are given.[14] Note that in the first period growers do not face the future consequences of their fungicide. In the second period, the profit function for grower $i$ is

$$\pi_{i2}(x_{i2}, f_{i2}, f_{i1}, f_{j1}) = pwx_{i2}^{\alpha}(f_{i2} - \theta[f_{i1} + f_{j1}])^{\beta} - cx_{i2} - zf_{i2}. \tag{5}$$

[14]Seccia et al. (2015) discuss that the global market for table grapes has generally become more competitive over the years. In this regard, this assumption coincides. If we consider grapes as inputs, Richards and Patterson (2003) suggest that, in light of their findings, growers have relatively low power to determine prices.

In period 2, profits are negatively affected by the fungicide choices of both growers in the previous period. Therefore, the general structure of the game is: (i) in stage 1, every grower $i$ simultaneously chooses inputs, $x_{i1}$ and $f_{i1}$ and (ii) in stage 2, every grower $i$ simultaneously chooses $x_{i2}$ and $f_{i2}$ and faces the fungicide resistance resulting from aggregate fungicide use in period 1. To address the negative intertemporal production externality that fungicide use generates, we examine a compensation mechanism of the following form: grower $i$ voluntarily restricts fungicide use provided that grower $j$ compensates him for his lost profits. We extend our discussion of the compensation mechanism in Section 2.2. Next, we examine what occurs if growers face fungicide resistance without a compensation mechanism.

## 2.1 Fungicide Resistance without the Compensation Mechanism

To begin, we examine the two-stage game without compensation. Profits for periods 1 and 2 correspond with equations (4) and (5), respectively. We consider that profits in stage 2 are discounted by $\delta \in (0, 1]$. For simplicity, for the remainder of our analysis we assume that $\alpha > \beta$, which facilitates the provision of meaningful results. The model in Section 2.2 becomes intractable if we allow for general values of these parameters.[15] We next solve the game using backward induction.

In the second stage, growers choose their input levels to maximize their respective profits for period 2 in the game. Given the intertemporal nature of the production externality, each grower $i$ obtains a best-response function capturing the choices of fungicide levels in the first period, which we present in the following lemma.

[15] With the Cobb-Douglas production technology, $\alpha$ and $\beta$ represent the output elasticities of the inputs to grape production. We assign a relatively greater elasticity of output (i.e., $\alpha > \beta$) to all other inputs rather than to fungicide because grape production is more sensitive to all of the other inputs in conjunction than to fungicide alone. We consider $\alpha = \frac{1}{2}$ and $\beta = \frac{1}{4}$, but the results are not qualitatively affected if we consider different values for $\alpha$ and $\beta$ as long as $\alpha > \beta$ and $\alpha + \beta < 1$.

Lemma 1. *In the second period every grower $i$ chooses*

$$f_{i2}(f_{i1}, f_{j1}) = \frac{p^4 w^4}{64c^2 z^2} + \theta(f_{i1} + f_{j1}) \text{ and}$$

$$x^*_{i2} = \frac{p^4 w^4}{32c^3 z}.$$

Therefore, the fungicide levels in the second period are increasing in the aggregate fungicide levels in the first period. This represents growers' adjustment of their second-period levels of fungicide use given the fungicide resistance stemming from period 1.

In the first stage, growers choose their input levels to maximize the present value of their profits. The equilibrium results are presented in the following proposition.

Proposition 1. *The equilibrium levels of fungicide, $f^*_{it}$, and all other inputs, $x^*_{it}$, for every grower $i$ are*

*(i) in period 1:*

$$f^*_{i1} = \frac{p^4 w^4}{64c^2 z^2 (1 + \delta\theta)^2} \text{ and } x^*_{i1} = \frac{p^4 w^4}{32c^3 z(1 + \delta\theta)};$$

*(ii) in period 2:*

$$f^*_{i2} = \frac{p^4 w^4 (1 + 2\theta[1 + \delta] + \delta^2\theta^2)}{64c^2 z^2 (1 + \delta\theta)^2} \text{ and } x^*_{i2} = \frac{p^4 w^4}{32c^3 z};$$

*where input levels in both periods are strictly positive for any nonnegative price. In addition, $f_{i1} < f_{i2}$, $x_{i1} < x_{i2}$ and $f_{it}$ is decreasing in $\theta$ for every period $t$.*

In this context, the levels of fungicide and other inputs are unambiguously higher in period 2 than in period 1. This relationship stems from the nature of fungicide resistance; namely, it manifests as a negative production externality which requires increased applications of fungicide in the period where the externality is present.

We are concerned with how different the levels are from the socially optimal fungicide levels. To make this comparison, we must first determine the socially optimal levels of inputs.

We consider that a social planner (e.g., a growers' association) maximizes the aggregate discounted profits of both growers. In the next lemma, we present the optimal input levels associated with the social planner's problem.

LEMMA 2. *The socially optimal input levels for every grower $i$ are*

*(i) in period 1:*

$$f_{i1}^{SO} = \frac{p^4 w^4}{64c^2 z^2 (1 + 2\delta\theta)^2} \text{ and } x_{i1}^{SO} = \frac{p^4 w^4}{32c^3 z (1 + 2\delta\theta)};$$

*(ii) in period 2:*

$$f_{i2}^{SO} = \frac{p^4 w^4 \left(1 + 2\theta[1 + 2\delta] + 4\delta^2\theta^2\right)}{64c^2 z^2 (1 + 2\delta\theta)^2} \text{ and } x_{i2}^{SO} = \frac{p^4 w^4}{32c^3 z}.$$

Similar to the results in Proposition 1, socially optimal first-period fungicide levels are strictly decreasing in the severity of fungicide resistance. In the following corollary we discuss the comparison of aggregate fungicide levels in the case without the compensation mechanism and the social planner's problem (Lemma 2).

COROLLARY 1. *For all admissible parameter values, fungicide levels are socially excessive.*

This relationship between the equilibrium levels in the game without compensation and the socially optimal levels are largely explained by the planner's internalization of the intertemporal externality. Every grower $i$ internalizes the negative effect of $f_{i1}$ on his own second-period profits, but ignores the effect of $f_{i1}$ on grower $j$'s second-period profits. This is the only external effect that the social planner helps to internalize (given that the other effect is taken care of by each grower). That is, because the social planner considers both growers' discounted profits in their maximization, they internalize the effects of fungicide resistance and respond by reducing inputs in both periods. In the next section, we propose a mechanism that induces the socially optimal levels of fungicide.

## 2.2 Fungicide Resistance with the Compensation Mechanism

In this context, we consider that growers $i$ and $j$ enter an agreement where only grower $i$ limits his fungicide level in the first period, which helps to mitigate the fungicide resistance severity experienced in period 2. Given that grower $i$ cannot freely choose their own fungicide level in period 1, the agreement requires grower $j$ (who chooses grower $i$'s period 1 fungicide level) to compensate grower $i$ in period 2.[16]

To begin, we determine a compensation level that leads both growers to participate in the agreement. Such an acceptable transfer, $T$, is that which renders both growers indifferent between the lifetime profits without the compensation (see Proposition 1) and those with the compensation. We begin by examining the condition that must be true for grower $i$ to participate; we determine what level of compensation is required to make grower $i$ indifferent between choosing fungicide without restriction and selecting with restriction,

$$\pi_{i1}(x_{i1}, f_{i1}^R) + \delta\pi_{i2}(x_{i2}, f_{i2}, f_{i1}^R, f_{j1}; T) \geq \sum_{t=1}^{2} \pi_{it}^*(\cdot), \tag{6}$$

where $\pi_{it}^*(\cdot)$ is the profit level for grower $i$ in the game without compensation mechanism (from Proposition 1) and $f_{i1}^R$ indicates grower $i$'s restricted fungicide level. The participation condition on $T$ for grower $j$, who requests a specific level for grower $i$'s period 1 fungicide, $f_{i1}^R$ , and makes the transfer, $T$, to grower $i$ is

$$\pi_{j1}(x_{j1}, f_{j1}) + \delta\pi_{j2}(x_{j2}, f_{j2}, f_{i1}^R, f_{j1}; T) \geq \sum_{t=1}^{2} \pi_{jt}^*(\cdot). \tag{7}$$

The period 1 profit equation remains the same as that in equation (4); however, grower $i$'s period 1 fungicide level is restricted. In the second period, however, the profit functions for

[16]We consider an alternative mechanism for correcting growers' use of fungicide given that Skevas et al. (2012) demonstrate empirically that taxes insufficiently reduce pesticide use and to avoid the problem of requiring the involvement of a perfectly-informed central planner (as is required for the subsidy mechanism in Martin (2015), for example).

grower $i$ and $j$ are

$$\pi_{i2}(x_{i2}, f_{i2}, f_{i1}^R, f_{j1}) = pw(x_{i2})^\alpha (f_{i2} - \theta[f_{i1}^R + f_{j1}])^\beta - cx_{i2} - zf_{i2} + T \text{ and}$$

$$\pi_{j2}(x_{i2}, f_{i2}, f_{i1}^R, f_{j1}) = pw(x_{j2})^\alpha (f_{j2} - \theta[f_{i1}^R + f_{j1}])^\beta - cx_{j2} - zf_{j2} - T.$$

Here, though grower $i$ is being restricted in period 1 fungicide levels, he is compensated by grower $j$ for any resulting loss of profits. We solve by backward induction and the results of this case are presented in the following proposition.

PROPOSITION 2. *The equilibrium levels of fungicide and all other inputs for every grower i when there is the compensation mechanism are*

*(i) in period 1:*

$$\hat{f}_{i1}^R = \frac{p^4 w^4}{64c^2 z^2 (1 + 2\delta\theta)^2} \text{ and } \hat{x}_{i1} = \frac{p^4 w^4}{32c^3 z (1 + 2\delta\theta)};$$

*(ii) in period 2:*

$$\hat{f}_{i2} = \frac{p^4 w^4 \left(1 + 2\theta[1 + 2\delta] + 4\delta^2\theta^2\right)}{64c^2 z^2 (1 + 2\delta\theta)^2} \text{ and } \hat{x}_{i2} = \frac{p^4 w^4}{32c^3 z}.$$

These levels are strictly positive for all admissible parameter values. As before, we are concerned with how close these levels are to socially optimal levels (Lemma 2). In the following corollary, we address the question.

COROLLARY 2. *The compensation mechanism leads to socially optimal input levels.*

Therefore, the compensation mechanism induces growers to internalize the intertemporal externality, which in turn leads them to choose the socially optimal input levels.[17] We next identify the compensation in equilibrium.

[17]This result is maintained if grower $i$ is asked to choose the socially optimal fungicide level in period 1 and compensated for the change in either period 1 or period 2. The solutions to these variations can be provided upon request by the authors.

Lemma 3. *The optimal compensation is*

$$\hat{T} = \frac{p^4 w^4 \left[\delta\theta\left(\delta\theta\left[2\delta\theta\left(\gamma^{\frac{1}{2}} - 4\right) + 11\gamma^{\frac{1}{2}} - 20\right] + 4\left[3\gamma^{\frac{1}{2}} - 4\right]\right) + 4\left(\gamma^{\frac{1}{2}} - 1\right)\right]}{64\delta z \gamma^{5/2} c^2 (1+\delta\theta)^2},$$

*where* $\gamma = 1 + 2\delta\theta$ *and* $\hat{T}$ *is positive for all admissible parameter values.*

This exact compensation renders grower $i$ willing to limit inputs in period 1 to socially optimal levels. In the next section, we consider that grower $j$ is misinformed about the severity of fungicide resistance.

# 3 Misinformation about Fungicide Resistance Severity

In this section, we examine what occurs when we apply the compensation mechanism in a context in which a grower incorrectly estimates, or holds incorrect beliefs about, fungicide resistance severity. Oliver et al. (2021) discuss that the need for information about fungicide resistance and mitigation for grape growers is a possibly increasing problem for the US grape industry. In our context, a grower who is misinformed about fungicide resistance severity, as discussed in Kuklinski et al. (2000), "confidently hold[s] wrong beliefs." This confidence distinguishes a misinformed grower from an uncertain grower, and we therefore model it distinctly. We next evaluate the scenario where the grower who provides the compensation, grower $j$, is misinformed.

## 3.1 Compensating Grower $j$ is Misinformed

We consider first that grower $i$ knows the true severity of fungicide resistance, but grower $j$ is misinformed. This situation can occur if grower $i$, but not grower $j$, is very experienced or has access to expert crop consultants, for example. That is, rather than knowing the true future fungicide resistance severity, $\theta$, grower $j$ wrongly believes that fungicide resistance severity is $\theta_m$ (where $\theta_m \neq \theta$). Otherwise, we maintain the same assumptions on the production function and structure of the game without and with the compensation mechanism. We next examine the equilibrium results with no compensation.

PROPOSITION 3. *The equilibrium levels of fungicide and all other inputs for growers i and j, when grower j is misinformed and there is no compensation, are*

*(i) in period 1:*

$$\bar{f}_{i1} = \frac{p^4 w^4}{64c^2 z^2 (1+\delta\theta)^2} \text{ and } \bar{f}_{j1} = \frac{p^4 w^4}{64c^2 z^2 \left(1+\delta\theta_m\right)^2};$$

$$\bar{x}_{i1} = \frac{p^4 w^4}{32c^3 z (1+\delta\theta)} \text{ and } \bar{x}_{j1} = \frac{p^4 w^4}{32c^3 z \left(1+\delta\theta_m\right)};$$

*(ii) in period 2:*

$$\bar{f}_{i2} = \frac{p^4 w^4 \left(1+\theta\left[\frac{1}{(1+\delta\theta)^2}+\frac{1}{(1+\delta\theta_m)^2}\right]\right)}{64c^2 z^2} \text{ and } \bar{f}_{j2} = \frac{p^4 w^4 \left(1+\theta_m\left[\frac{1}{(1+\delta\theta)^2}+\frac{1}{(1+\delta\theta_m)^2}\right]\right)}{64c^2 z^2};$$

$$\bar{x}_{i2} = \bar{x}_{j2} = \frac{p^4 w^4}{32c^3 z};$$

*where input levels in both periods are strictly positive for any nonnegative price.*

Similar to the previous section, grower $i$'s choice of fungicide level is too high relative to the socially optimal in period 1 given that he knows the true value of $\theta$ (because they are not forced to internalize the externality). We are especially concerned with how grower $j$'s misinformation about the fungicide resistance severity affects his period 1 choice of fungicide level compared to Lemma 2. In the following corollary, we summarize some of the findings.

COROLLARY 3. *When $\theta_m > 2\theta$ ($\theta_m < 2\theta$), the grower j's use of fungicide in period 1 is socially insufficient (excessive, respectively) without compensation. Their fungicide use coincides with the socially optimal level when $\theta_m = 2\theta$.*

Upon examination, we find that if grower $j$ estimates that fungicide resistance is more than twice as severe as it is in reality ($\theta_m > 2\theta$), then he chooses a fungicide level that is strictly lower than socially optimal (see Figure 1, Region $A$). Conversely, grower $j$ chooses a socially excessive amount if he considers that the severity is less than twice what it is in reality ($\theta_m < 2\theta$, see Figure 1, Region $B$). In this context, grower $j$ chooses the socially-optimal fungicide level in period 1 if he considers that fungicide resistance is twice as severe as it actually is ($\theta_m = 2\theta$, see Figure 1).[18] Therefore, the misinformation would inadvertently lead the misinformed grower to select the socially optimal choice, making the presence of compensation unnecessary.

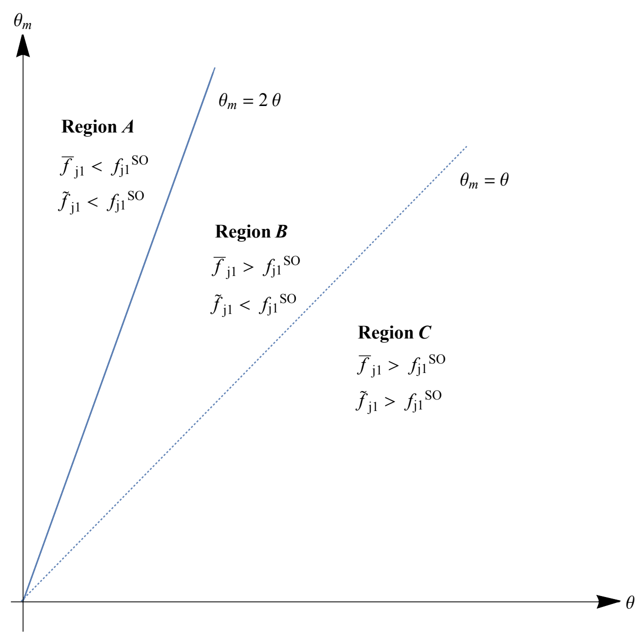


Figure 1: Grower $j$ is misinformed.

In the following proposition, we present the results allowing for compensation.

Proposition 4. *The equilibrium levels of fungicide and all other inputs for growers $i$ and $j$, when grower $j$ is misinformed but there is compensation, are*

[18]We also examined the case where growers coordinate to maximize aggregate profits, but grower $j$ remains misinformed about fungicide resistance severity. This "second-best" socially optimal scenario coincides with the first-best socially optimal above if $\theta = \theta_m$. Misinformation leads grower $j$ to choose a fungicide level in period 1 that is strictly higher than that in the second-best case.

*(i) in period 1:*

$$\widetilde{f}_{i1}^{R} = \widetilde{f}_{j1} = \frac{p^4 w^4}{64c^2 z^2 \left(1+\delta[\theta+\theta_m]\right)^2};$$

$$\widetilde{x}_{i1} = \widetilde{x}_{j1} = \frac{p^4 w^4}{32c^3 z \left(1+\delta[\theta+\theta_m]\right)};$$

*(ii) in period 2:*

$$\widetilde{f}_{i2} = \frac{p^4 w^4 \left(\frac{2\theta}{[1+\delta(\theta+\theta_m)]^2}+1\right)}{64c^2 z^2} \text{ and } \widetilde{f}_{j2} = \frac{p^4 w^4 \left(\frac{2\theta_m}{[1+\delta(\theta+\theta_m)]^2}+1\right)}{64c^2 z^2};$$

$$\widetilde{x}_{i2} = \widetilde{x}_{j2} = \frac{p^4 w^4}{32c^3 z};$$

*where input levels in both periods are strictly positive for any nonnegative price.*

The following lemma presents the optimal compensation when grower $j$ is misinformed, $\widetilde{T}$.

LEMMA 4. *The optimal compensation when the compensating grower $j$ is misinformed is*

$$\widetilde{T} = \frac{\delta p^4 w^4 \left(\theta_m^2\left[\delta^2\theta_m^2+2\delta\theta_m+1\right]-2\delta\theta^2\theta_m\left[1+\delta\theta\right]-\theta^2\left[\delta^2\theta^2+3\delta\theta+2\right]\right)}{64c^2 z(1+\delta\theta)\left(1+\delta\theta_m\right)^2\left(1+\delta\theta+\delta\theta_m\right)^2}.$$

*In addition, $\theta_m > \theta$ is a necessary condition for $\widetilde{T} > 0$.*

Figure 2 compares both $\hat{T}$, the optimal transfer under complete information, and $\widetilde{T}$, the optimal transfer with a misinformed grower $j$.[19]

[19] We consider the parameter values: $\theta_m = \frac{3}{4}, p = 1, w = 1, c = \frac{1}{2}, z = \frac{1}{2}, \delta = 1$.

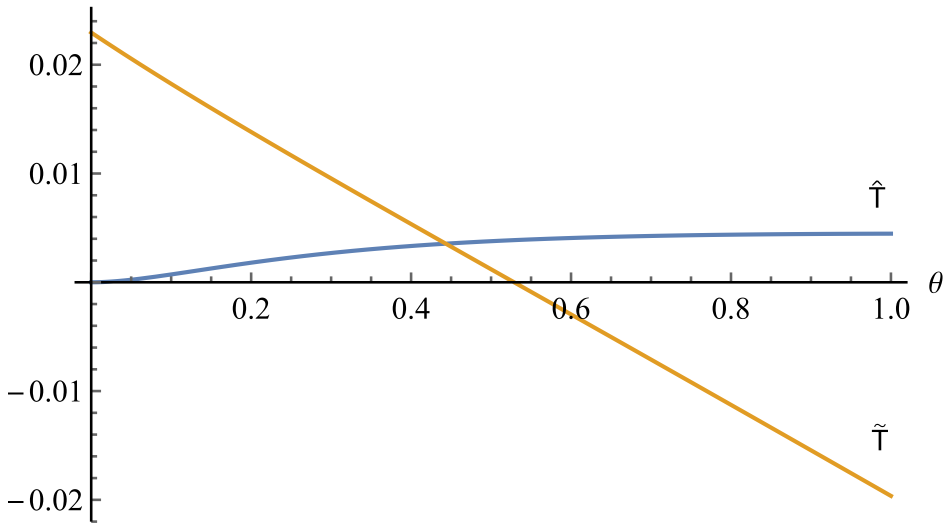


Figure 2: Optimal compensations in complete information and misinformation with $\theta_m = \frac{3}{4}$.

We observe that when the misinformed grower overestimates the severity of fungicide resistance, $\theta < \theta_m = \frac{3}{4}$, and the true severity of fungicide resistance is relatively mild, then $\widetilde{T} > \hat{T}$. In this case, grower $j$ overcompensates grower $i$ for a reduction of fungicide, which is mainly explained by a more demanding reduction of fungicide (i.e., $\widetilde{f}_{i1}^R < \hat{f}_{i1}^R$). However, an underestimation of fungicide resistance severity, $\theta > \theta_m = \frac{3}{4}$, induces zero compensation implying that $\widetilde{T} < \hat{T}$ (note that we only consider positive transfers). To understand the inefficiencies produced by misinformation on the compensation mechanism, we discuss grower $j$'s period 1 fungicide levels and provide a corollary to summarize.

Corollary 4. *When $\theta_m > \theta$ ($\theta_m < \theta$), grower $j$'s period 1 use of fungicide is socially insufficient (excessive, respectively) under compensation.*

If grower $j$ estimates that fungicide resistance is more severe than it is in reality ($\theta_m > \theta$), then his period 1 fungicide level choice is always lower than the socially optimal level (see Figure 1, regions $A$ and $B$). If instead grower $j$ considers that fungicide resistance is less severe than in reality ($\theta_m < \theta$), then grower $j$'s period 1 fungicide level is higher than socially optimal (see Figure 1, Region $C$) . It would only coincide with the socially optimal level if the compensating grower was not misinformed.[20]

Therefore, the compensation mechanism's effectiveness depends critically upon both growers being well informed about the future severity of fungicide resistance. Our analysis suggests that if the compensating grower cannot be fully informed, then it is somewhat better if he estimates that the externality is more severe than it is in reality (i.e., grower $j$ has pessimistic assumptions about the impact of future fungicide resistance on production). This implies that if the objective is to reduce fungicide resistance in the future, it is most important that the grower who provides compensation, and exerts some control over the input choices of the other, does not underestimate the severity of fungicide resistance.

## 3.2 Compensated Grower $i$ is Misinformed

In contrast to the previous scenario, we now evaluate the case wherein the grower who receives the compensation, grower $i$, is misinformed about the severity of fungicide resistance.[21] Next, we share the equilibrium results associated with this scenario and focus on the case with compensation.[22]

PROPOSITION 5. *The equilibrium levels of fungicide and all other inputs for growers i and j, when grower i is misinformed but there is a compensation mechanism, are*

*(i) in period 1:*

$$\check{f}_{i1}^{R} = \frac{p^4 w^4 \left(13\delta\theta - 7\delta\theta_m + 3\right)^2}{576 c^2 z^2 \left(\delta[3\theta - \theta_m] + 1\right)^4} \text{ and } \check{f}_{j1} = \frac{p^4 w^4}{64 c^2 z^2 \left(\delta[3\theta - \theta_m] + 1\right)^2};$$

[20] Though this compensation mechanism fails to attain the socially optimal levels (in terms of the first-best scenario where there is no misinformation), it succeeds in bringing grower $j$'s optimal fungicide level to the second-best scenario (where growers maximize aggregate profits but one grower remains misinformed).

[21] The results associated with no compensation mechanism when grower $i$ is misinformed exactly coincide with those in the previous subsection (when grower $j$ is misinformed and there is no compensation mechanism).

[22] We present and interpret only the scenario where grower $i$ chooses strictly positive input levels in period 1 ($0 < \theta_m < \frac{13\delta\theta+3}{7\delta}$).

$$\check{x}_{i1} = \frac{p^4 w^4 \left(13\delta\theta - 7\delta\theta_m + 3\right)^3}{864 c^3 z \left(\delta[3\theta - \theta_m] + 1\right)^4} \text{ and } \check{x}_{j1} = \frac{p^4 w^4}{32 c^3 z \sqrt{(\delta[3\theta - \theta_m] + 1)^2}};$$

*(ii) in period 2:*

$$\check{f}_{i2} = \theta_m \check{f}_{i1}^R + \frac{9p^4 w^4}{576 c^2 z^2} \left( \frac{\theta_m + [\delta(3\theta - \theta_m) + 1]^2}{[\delta(3\theta - \theta_m) + 1]^2} \right) \text{ and}$$

$$\check{f}_{j2} = \theta \check{f}_{i1}^R + \frac{9p^4 w^4}{576 c^2 z^2} \left( \frac{\theta + [\delta(3\theta - \theta_m) + 1]^2}{[\delta(3\theta - \theta_m) + 1]^2} \right);$$

$$\check{x}_{i2} = \check{x}_{j2} = \frac{p^4 w^4}{32 c^3 z};$$

*where input levels in both periods are strictly positive for any nonnegative price.*

Note that the optimal transfer in this context is presented in the Appendix. As in Subsection 3.1, grower $i$'s first-period fungicide level in this scenario is always socially excessive when the wrong beliefs about fungicide resistance severity are not so pessimistic that they halt production in period 1 (i.e., if $0 < \theta_m < \frac{13\delta\theta+3}{7\delta}$). We include the following corollary to summarize some of the comparative statics associated with our results.

Corollary 5. *When the grower who provides (receives) compensation is misinformed, aggregate period 1 levels are decreasing (increasing, respectively) in the misinformed fungicide resistance severity.*

We observe that aggregate period 1 fungicide levels are strictly decreasing in the misinformed fungicide resistance severity when grower $j$ is misinformed (i.e., Subsection 3.1). That is to say that the more severe the misinformed grower estimates fungicide resistance to be, the lower the aggregate fungicide usage in period 1. This directly contrasts with the scenario when the grower who receives compensation is misinformed (i.e., in Subsection 3.2). In this case, the first-period aggregate usage is strictly increasing in the misinformed fungicide resistance severity (please see Table 1 for a summary of these relationships). To better understand this, it is informative to examine how each grower adjusts period 1 fungicide usage when the misinformed grower's assumption changes about fungicide resistance severity. Specifically, the period 1 fungicide usage for the grower who provides compensation and is *informed* (i.e., grower $j$), strictly increases in how severe grower $i$ estimates the externality is (i.e., $\theta_m$). This response is the driver of the positive relationship between aggregate fungicide use and the misinformed fungicide resistance severity.

Table 1: Aggregate Period 1 Fungicide Levels Comparative Statics

| | Grower $i$ Misinformed | Grower $j$ Misinformed |
|---|---|---|
| Misinformed fungicide resistance severity, $\theta_m$ | + | - |

For growers who seek to apply the compensation mechanism to address the problem of fungicide resistance, the first-best scenario would be that all growers are perfectly informed about fungicide resistance severity (e.g., via accessible and accurate testing and forecasts along with effective education). In the context of misinformation, the effectiveness of the compensation mechanism is largely dictated by what the misinformed grower assumes about fungicide resistance severity and what role they have in the compensation mechanism. If, for example, the goal is to reduce the misinformed grower's fungicide usage, then it is better when the misinformed grower provides compensation (i.e., a misinformed grower $j$ as in Subsection 3.1). The scenario in Subsection 3.2 leads to strictly higher than socially optimal fungicide levels chosen by the misinformed grower. These findings demonstrate the importance of educational outreach to growers about fungicide resistance. Further, they provide awareness to associations of growers seeking to reduce future fungicide resistance before all growers are fully informed. The following subsection contains an analysis of social welfare in the context of misinformation.

## 3.3 Social Welfare Analysis

We evaluate which circumstances lead to higher levels of aggregate profits (which constitute social welfare in this analysis). We do so by comparing the aggregate profits under both cases of misinformation with compensation to those in the social planner's problem (Lemma 2). To facilitate comparisons that provide guidance for growers seeking to apply the compensation mechanism, for the remainder of this subsection we provide two numerical examples illustrating relatively mild and severe fungicide resistance, respectively.[23]

Corollary 6. *Under misinformation, in either mild or severe fungicide resistance, social welfare is lower with the compensation mechanism than in the social planner's problem.*

To illustrate a portion of the above corollary, we include Figure 3 showing the differences in social welfare for relatively mild fungicide resistance between the social planner's problem, $SW_{SP}$ and the corresponding misinformation scenarios with compensation (i.e., Figure 3 compares the social welfare of the social planner's problem with that of subsection 3.1, $SW_{Misinf.Compensator}$, and compares it with subsection 3.2, $SW_{Misinf.Compensatee}$, respectively). It shows that regardless of whether grower $j$ or grower $i$ is misinformed, the curve representing the difference between the social welfare in the social planner's problem and the case of misinformation with compensation always lies in the positive quadrant. This implies that, in either case, social welfare in the social planner's problem is strictly greater except when both growers are well informed (i.e., $\theta_m = \theta$). This is mirrored in the case of severe fungicide resistance.

[23]Where for the mild case we consider: $\theta = \frac{1}{4}, p = 1, w = 1, c = \frac{1}{2}, z = \frac{1}{2}, \delta = 1$. For the severe case we consider $\theta = \frac{3}{4}$ and hold the other parameters constant. We provide different parameter comparisons in the Appendix, see figures 6-9. Our results are qualitatively unchanged.

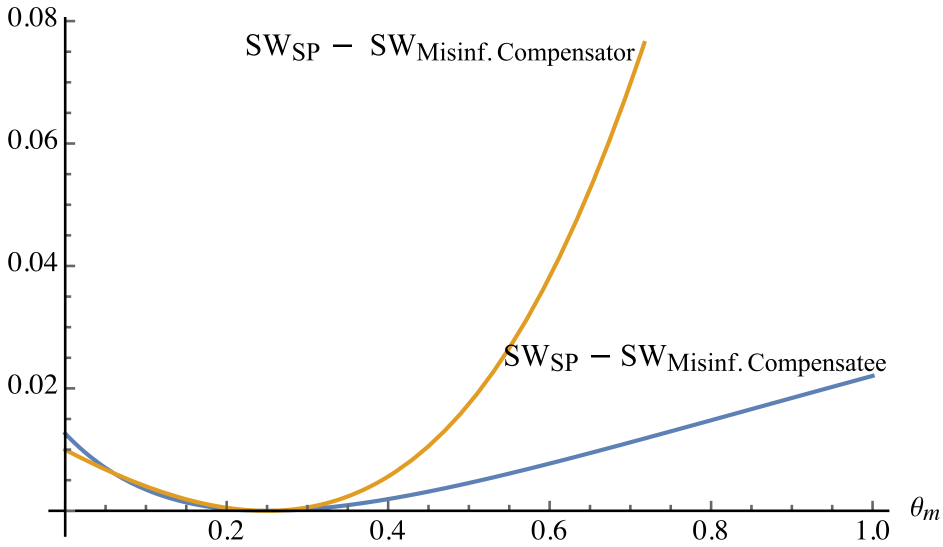


Figure 3: Differences between socially optimal welfare and welfare with compensation and misinformation.

Therefore, as noted in Corollary 6, the compensation mechanism cannot bring aggregate profits to the socially optimal level when there is misinformation. If misinformation is inevitable, we examine the change in social welfare considering that grower $i$ or $j$ is misinformed. We include Figure 4 to illustrate the differences between social welfare in the scenarios illustrated in subsections 3.1 and 3.2 under mild and severe fungicide resistance, respectively,[24] as a grower's misinformed assumption about fungicide resistance severity changes.

[24]This is equivalent to the difference between aggregate profits in Subsection 3.2 and aggregate profits in Subsection 3.1. Therefore, if the curve is in the positive quadrant, then social welfare is higher in the scenario in Subsection 3.2 than in Subsection 3.1.

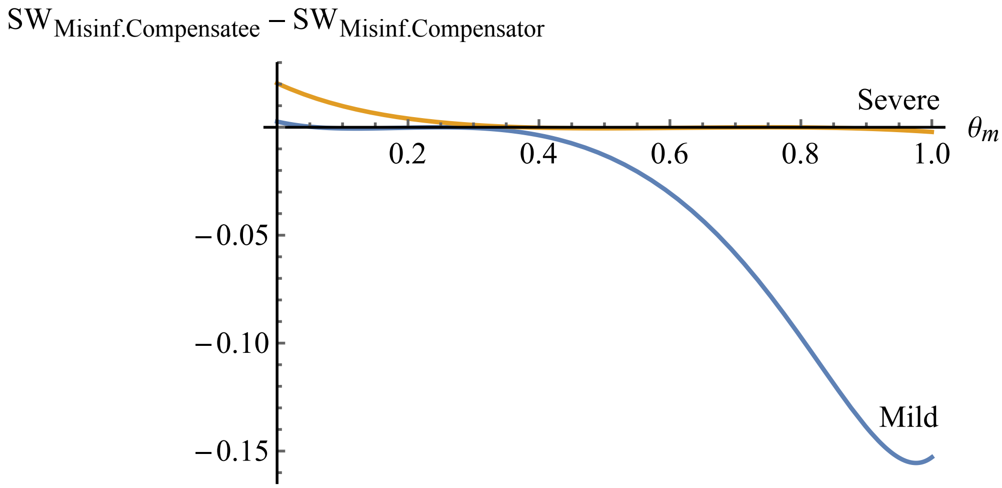


Figure 4: Differences in social welfare between possible scenarios.

We observe that if the misinformed grower considers fungicide resistance to be more severe than it actually is ($\theta_m > \theta$), it is better if the misinformed grower provides compensation (i.e., Subsection 3.1). Generally, growers' welfare is higher if the grower who provides compensation is the one who is misinformed (i.e., for a wider range of misinformed fungicide resistance severities, social welfare is higher in Subsection 3.1). However, for certain levels of optimistic misinformation ($\theta_m < \theta$), it is better if the informed grower provides compensation (i.e., in Subsection 3.2, social welfare is higher when the misinformed grower considers that fungicide resistance is particularly mild). The figures also illustrate that the lower the level of misinformation, the smaller the difference between the scenarios associated with each subsection. That is, when the misinformed grower considers fungicide resistance severity to be relatively close to its true value, then the compensation mechanism's effectiveness is less dependent on whether the misinformed grower provides or receives compensation (i.e., social welfare is less sensitive to which scenario, Subsection 3.1 or Subsection 3.2, occurs).

# 4 Conclusion

We examine the consequences of the intertemporal production externality of fungicide resistance for grape growers. We design a compensation mechanism in which a grower restricts his fungicide usage and his neighboring grower compensates him. We find that growers internalize the externality and choose socially optimal fungicide levels under complete information. Without the mechanism, however, they fail to internalize the externality of fungicide resistance and choose fungicide levels that are socially excessive.

Our results also indicate that the effectiveness of the compensation mechanism in reducing aggregate fungicide levels, and in turn fungicide resistance, is critically dependent upon the information available to growers about future fungicide resistance severity. Therefore, efforts to predict fungicide resistance severity and to communicate that information to growers are essential for mitigating fungicide resistance with our proposed compensation mechanism. However, when one grower is misinformed, the compensation mechanism can reduce the aggregate first-period fungicide level below the socially optimal level. This can occur if the grower who provides compensation considers that fungicide resistance is more severe than it truly is.

In terms of social welfare, the most preferable scenario is that all growers are perfectly informed about fungicide resistance severity. In the context of misinformation, we provide additional awareness about the circumstances contributing to the relative effectiveness of a social welfare improving compensation mechanism. Our findings suggest that if misinformation persists among some growers, it is often better if the misinformed grower provides compensation. If the misinformed grower considers fungicide resistance to be more severe than it actually is, then it is always better if they provide the compensation. These findings similarly signal the importance of improving the access to accurate information about fungicide resistance for growers who participate in this compensation mechanism.

We consider that growers have already accepted the terms of the compensation mechanism, which requires that one grower accept the compensating role while the other reduces fungicide levels and receives compensation. The assignment is aleatory since growers are symmetric. Hence, considering a context in which an association of growers can decide the role of each grower in the agreement would be a natural extension. This becomes especially relevant when growers are asymmetric. An additional avenue for future work that arises from our paper is examining the context wherein a well-informed grower can signal the true state of fungicide resistance severity to a neighboring grower.

# References

Alpizar, F., F. Carlsson, and M. A. Naranjo (2011). The effect of ambiguous risk, and coordination on farmers' adaptation to climate change - A framed field experiment. *Ecological Economics 70*(12), 2317–2326. 5

Ambec, S. and M. Desquilbet (2012). Regulation of a spatial externality: Refuges versus tax for managing pest resistance. *Environmental and Resource Economics 51*(1), 79–104. 1, 3

Bhat, M. G. and R. G. Huffaker (2007). Management of a transboundary wildlife population: A self-enforcing cooperative agreement with renegotiation and variable transfer payments. *Journal of Environmental Economics and Management 53*(1), 54–67. 2

Carlson, G. A. (1977). Long-run productivity of insecticides. *American Journal of Agricultural Economics 59*(3), 543–548. 7

Christ, K. L. and R. L. Burritt (2013). Critical environmental concerns in wine production: An integrative review. *Journal of Cleaner Production 53*, 232–242. 1

Cobourn, K. M., G. S. Amacher, and R. G. Haight (2019). Cooperative management of invasive species: A dynamic nash bargaining approach. *Environmental and Resource Economics 72*(4), 1041–1068. 3

Cornes, R., N. Van Long, and K. Shimomura (2001). Drugs and pests: Intertemporal production externalities. *Japan and the World Economy 13*(3), 255–278. 1, 3

Corwin, J. A. and D. J. Kliebenstein (2017). Quantitative resistance: More than just perception of a pathogen. *Plant Cell 29*(4), 655–665. 1

Desquilbet, M. and M. Herrmann (2016). The Dynamics of Pest Resistance Management: The Case of Refuge Fields for Bt Crops. *Canadian Journal of Agricultural Economics 64*(2), 253–288. 1

Finger, R., N. Möhring, T. Dalhaus, and T. Böcker (2017). Revisiting pesticide taxation schemes. *Ecological Economics 134*, 263–266. 3

Gianessi, L. and N. Reigner (2006). The importance of fungicides in U.S. crop production. *Outlooks on Pest Management 17*(5), 209–213. 1

Goeb, J., A. Dillon, F. Lupi, and D. Tschirley (2020). Pesticides: What you don't know can hurt you. *Journal of the Association of Environmental and Resource Economists*, 709–782. 5

Krishna, V. V., A. G. Drucker, U. Pascual, P. T. Raghu, and E. D. O. King (2013). Estimating compensation payments for on-farm conservation of agricultural biodiversity in developing countries. *Ecological Economics 87*, 110–123. 2

Kuklinski, J. H., P. J. Quirk, J. Jerit, D. Schwieder, R. F. Rich, J. H. Kuklinski, P. J. Quirk, J. Jerit, D. Schwieder, and R. F. Rich (2000). Misinformation and the currency of democratic citizenship. *The Journal of Politics 62*(3), 790–816. 13

Lemarié, S. and P. Marcoul (2018). Coordination and information sharing about pest resistance. *Journal of Environmental Economics and Management 87*, 135–149. 2

Liu, Y. and C. Sims (2016). Spatial-dynamic externalities and coordination in invasive species control. *Resource and Energy Economics 44*, 23–38. 2, 3

Lucchi, A. and G. Benelli (2018). Towards pesticide-free farming? Sharing needs and knowledge promotes Integrated Pest Management. *Environmental Science and Pollution Research 25*(14), 13439–13445. 2

Martin, E. (2015). Should we internalise inter-temporal production spillovers in the case of pest resistance? *European Review of Agricultural Economics 42*(4), 539–578. 1, 2, 3, 6, 11

Oliver, C. L., M. L. Cooper, M. L. Lewis Ivey, P. M. Brannen, T. D. Miles, W. F. Mahaffee, and M. M. Moyer (2021). Assessing the United States Grape Industry's Understanding of Fungicide Resistance Mitigation Practices. *American Journal of Enology and Viticulture 72*(2), 181–193. 13

Oliver, R. and H. Hewitt (2014). *Fungicides in crop protection* (2 ed.). Boston, MA: CABI. 3

Pimentel, D. (2005). Environmental and economic costs of the application of pesticides primarily in the United States. *Environment, Development and Sustainability 7*(2), 229–252. 1

Regev, U., H. Shalit, and A. P. Gutierrez (1983). On the optimal allocation of pesticides with increasing resistance: The case of alfalfa weevil. *Journal of Environmental Economics and Management 10*(1), 86–100. 1, 2, 3

Richards, T. J. and P. M. Patterson (2003). Competition in fresh produce markets: An empirical analysis of marketing Cchannel performance. Technical Report September, United States Department of Agriculture. 7

Sambucci, O., J. M. Alston, K. B. Fuller, and J. Lusk (2019). The pecuniary and nonpecuniary costs of powdery mildew and the potential value of resistant grape varieties in California. *American Journal of Enology and Viticulture 70*(2), 177–187. 1

Sangkapitux, C., A. Neef, W. Polkongkaew, N. Pramoon, S. Nonkiti, and K. Nanthasen (2009). Willingness of upstream and downstream resource managers to engage in compensation schemes for environmental services. *International Journal of the Commons 3*(1), 41. 2

Seccia, A., F. G. Santeramo, and G. Nardone (2015). Trade competitiveness in table grapes: A global view. *Outlook on Agriculture 44*(2), 127–134. 7

Sexton, S. S., Z. Lei, and D. Zilberman (2007). The economics of pesticides and pest control. *International Review of Environmental and Resource Economics 1*(3), 271–326. 1, 7

Sims, C., D. Finnoff, and J. F. Shogren (2018). Taking one for the team: Is collective action more responsive to ecological change? *Environmental and Resource Economics 70*(3), 589–615. 2

Skevas, T., S. E. Stefanou, and A. O. Lansink (2012). Can economic incentives encourage actual reductions in pesticide use and environmental spillovers? *Agricultural Economics 43*(3), 267–276. 3, 11

Skevas, T., S. E. Stefanou, and A. O. Lansink (2013). Do farmers internalise environmental spillovers of pesticides in production? *Journal of Agricultural Economics 64*(3), 624–640. 3

Vielba-Fernández, A., Á. Polonio, L. Ruiz-Jiménez, A. de Vicente, A. Pérez-García, and D. Fernández-Ortuño (2020). Fungicide resistance in powdery mildew fungi. *Microorganisms 8*(9), 1–34. 1

# A Appendix

## A.1 Proof of Lemma 1

In period 2, grower $i$ solves

$$\max_{f_{i2},x_{i2}} \{pwx_{i2}^{\frac{2}{4}}(f_{i2} - \theta[f_{i1} + f_{j1}])^{\frac{1}{4}} - cx_{i2} - zf_{i2}\}.$$

Therefore, the first-order conditions for $x_{i2}$ and $f_{i2}$, respectively, for grower $i$ are

$$\frac{pw(f_{i2} - \theta[f_{i1} + f_{j1}])^{\frac{1}{4}}}{2\sqrt{x_{i2}}} - c = 0 \text{ and}$$

$$\frac{pw\sqrt{x_{i2}}}{4(f_{i2} - \theta[f_{i1} + f_{j1}])^{\frac{3}{4}}} - z = 0.$$

Utilizing the above conditions and solving for $f_{i2}(f_{i1}, f_{j1})$ yields

$$f_{i2}(f_{i1}, f_{j1}) = \theta(f_{i1} + f_{j1}) \pm \frac{p^4 w^4}{64c^2 z^2}.$$

We select the strictly positive values for our analysis. Using the best-response function the first-order condition for $x_{i2}$ provides us with the optimal value for other inputs in stage 2.

$$x_{i2}^* = \frac{p^4 w^4}{32c^3 z}.$$

## A.2 Proof of Proposition 1

In period 1, grower $i$ solves

$$\max_{f_{i1},x_{i1}} \{pwx_{i1}^{\frac{2}{4}} f_{i1}^{\frac{1}{4}} - cx_{i1} - zf_{i1} + \delta(pwx_{i2}^{\frac{2}{4}}(f_{i2} - \theta[f_{i1} + f_{j1}])^{\frac{1}{4}} - cx_{i2} - zf_{i2})\}.$$

Substituting in the expressions from Lemma 1 and simplifying, we obtain

$$\max_{f_{i1},x_{i1}}\{\frac{\delta p^4 w^4}{64c^2 z} - \delta z\theta\,(f_{i1}+f_{j1}) - cx_{i1} + pw(f_{i1})^{\frac{1}{4}}\sqrt{x_{i1}} - zf_{i1}\}.$$

Therefore, the first-order conditions for $x_{i1}$ and $f_{i1}$, respectively, for grower $i$ are

$$\frac{pwf_{i1}^{\frac{1}{4}}}{2\sqrt{x_{i1}}} - c = 0 \text{ and}$$

$$\frac{pw\sqrt{x_{i1}}}{4f_{i1}^{\frac{3}{4}}} - z(1+\delta\theta) = 0.$$

Using the above conditions and the expression for $f_{i2}(f_{i1}, f_{j1})$ we obtain

(i) in period 1:

$$f_{i1}^* = \frac{p^4w^4}{64c^2z^2(1+\delta\theta)^2} \text{ and } x_{i1}^* = \frac{p^4w^4}{32c^3z(1+\delta\theta)};$$

(ii) in period 2:

$$f_{i2}^* = \frac{p^4w^4(1+2\theta[1+\delta]+\delta^2\theta^2)}{64c^2z^2(1+\delta\theta)^2} \text{ and } x_{i2}^* = \frac{p^4w^4}{32c^3z}.$$

## A.3 Proof of Lemma 2

The social planner chooses $x_{it}, x_{jt}, f_{it}$, and $f_{jt}$, for $t = 1, 2$ to maximize the sum of the growers' profits. In period 2, the social planner solves

$$\max_{f_{i2},x_{i2},f_{j2},x_{j2}}\{[pwx_{i2}^{\frac{2}{4}}(f_{i2}-\theta[f_{i1}+f_{j1}])^{\frac{1}{4}} - cx_{i2} - zf_{i2} + pwx_{j2}^{\frac{2}{4}}(f_{j2}-\theta[f_{i1}+f_{j1}])^{\frac{1}{4}} - cx_{j2} - zf_{j2}]\}.$$

For which the corresponding first-order conditions (we consider interior solutions) are

$$\frac{pw\sqrt[4]{f_{i2}-\theta\,(f_{i1}+f_{j1})}}{2\sqrt{x_{i2}}} - c = 0$$

$$\frac{pw\sqrt{x_{i2}}}{4\left(f_{i2}-\theta\left(f_{i1}+f_{j1}\right)\right)^{3/4}}-z=0$$

$$\frac{pw\sqrt[4]{f_{j2}-\theta\left(f_{i1}+f_{j1}\right)}}{2\sqrt{x_{j2}}}-c=0$$

$$\frac{pw\sqrt{x_{j2}}}{4\left(f_{j2}-\theta\left(f_{i1}+f_{j1}\right)\right)^{3/4}}-z=0.$$

From these first-order conditions we can find $x_{i2}^{SO}$ and $x_{j2}^{SO}$.

(i) for grower $i$:

$$x_{i2}^{SO}=\frac{p^4w^4}{32c^3z}\text{ and}$$

(ii) for grower $j$:

$$x_{j2}^{SO}=\frac{p^4w^4}{32c^3z}.$$

In period 1, the social planner solves

$$\max_{f_{it},x_{it},f_{jt},x_{jt}}\{pwx_{i1}^{\frac{2}{4}}f_{i1}^{\frac{1}{4}}-cx_{i1}-zf_{i1}+pwx_{j1}^{\frac{2}{4}}f_{j1}^{\frac{1}{4}}-cx_{j1}-zf_{j1}+\delta[pwx_{i2}^{\frac{2}{4}}(f_{i2}-\theta[f_{i1}+f_{j1}])^{\frac{1}{4}}-cx_{i2}-zf_{i2}$$

$$+pwx_{j2}^{\frac{2}{4}}(f_{j2}-\theta[f_{i1}+f_{j1}])^{\frac{1}{4}}-cx_{j2}-zf_{j2}]\}.$$

Substituting the equations found in period 2, we obtain the following first-order conditions

$$\frac{pw\sqrt[4]{f_{i1}}}{2\sqrt{x_{i1}}}-c=0$$

$$\frac{pw\sqrt{x_{i1}}}{4f_{i1}^{3/4}}-z(2\delta\theta+1)=0$$

$$\frac{pw\sqrt[4]{f_{j1}}}{2\sqrt{x_{j1}}}-c=0$$

$$\frac{pw\sqrt{x_{j1}}}{4f_{j1}^{3/4}} - z(2\delta\theta + 1) = 0.$$

These and the above conditions imply the following socially optimal levels of inputs

(i) in period 1:

$$f_{i1}^{SO} = \frac{p^4w^4}{64c^2z^2(1+2\delta\theta)^2} \text{ and } x_{i1}^{SO} = \frac{p^4w^4}{32c^3z(1+2\delta\theta)};$$

(ii) in period 2:

$$f_{i2}^{SO} = \frac{p^4w^4\left(1+2\theta[1+2\delta]+4\delta^2\theta^2\right)}{64c^2z^2(1+2\delta\theta)^2} \text{ and } x_{i2}^{SO} = \frac{p^4w^4}{32c^3z}.$$

## A.4 Proof of Corollary 1

Let us first compare fungicide levels in period 1.

$$f_{i1}^* \geq f_{i1}^{SO} \tag{8}$$

implies

$$\frac{p^4w^4}{64c^2z^2(1+\delta\theta)^2} \geq \frac{p^4w^4}{64c^2z^2(1+2\delta\theta)^2}. \tag{9}$$

This holds if $\theta \geq 0$, which is satisfied by the assumption we maintain that $\theta \in (0,1)$. In the second period we have that

$$f_{i2}^* \geq f_{i2}^{SO} \tag{10}$$

implies

$$\frac{p^4w^4(1+2\theta[1+\delta]+\delta^2\theta^2)}{64c^2z^2(1+\delta\theta)^2} \geq \frac{p^4w^4\left(1+2\theta[1+2\delta]+4\delta^2\theta^2\right)}{64c^2z^2(1+2\delta\theta)^2}. \tag{11}$$

This similarly holds given $\theta \in (0,1)$.

## A.5 Proof of Proposition 2

In period 2, grower $i$ solves

$$\max_{x_{i2},f_{i2}} \{pwx_{i2}^{\frac{2}{4}}(f_{i2}-\theta[f_{i1}^R+f_{j1}])^{\frac{1}{4}}-cx_{i2}-zf_{i2}+T\}.$$

$$\text{s.t. } \pi_{i1}(x_{i1},f_{i1}^R)+\delta\pi_{i2}(x_{i2},f_{i2},f_{i1}^R,f_{j1};T)+\pi_{j1}(x_{j1},f_{j1})+\delta\pi_{j2}(x_{j2},f_{j2},f_{i1}^R,f_{j1};T)$$
$$=\sum_{t=1}^{2}\pi_{it}^*(\cdot)+\pi_{jt}^*(\cdot)$$

Therefore, $T$ is

$$T=\frac{1}{2\delta}[cx_{i1}+c\delta x_{i2}-cx_{j1}-c\delta x_{j2}-\delta pw\sqrt{x_{i2}}\sqrt[4]{f_{i2}-\theta\left(f_{i1}^R+f_{j1}\right)}\sqrt{x_{j1}}$$

$$+\delta pw\sqrt{x_{j2}}\sqrt[4]{f_{j2}-\theta\left(f_{i1}^R+f_{j1}\right)}-pw\sqrt[4]{f_{i1}^R}\sqrt{x_{i1}}+zf_{i1}^R+\delta zf_{i2}-z\left(f_{j1}+\delta f_{j2}\right)+pw\sqrt[4]{f_{j1}}].$$

The first-order conditions for $x_{i2}$ and $f_{i2}$, respectively, for grower $i$ are

$$\frac{1}{4}\left(\frac{pw\sqrt[4]{f_{i2}-\theta\left(f_{i1}^R+f_{j1}\right)}}{\sqrt{x_{i2}}}-2c\right)=0$$

$$\frac{1}{8}\left(\frac{pw\sqrt{x_{i2}}}{\left(f_{i2}-\theta\left(f_{i1}^R+f_{j1}\right)\right)^{3/4}}-4z\right)=0$$

Using the above conditions we obtain

$$\hat{x}_{i2}=\frac{p^4w^4}{32c^3z} \text{ and } f_{i2}(f_{i1}^R,f_{j1})=\theta(f_{i1}^R+f_{j1})\pm\frac{p^4w^4}{64c^2z^2}.$$

We select the strictly positive values for our analysis. In period 2, grower $j$'s choose $x_{j2}$ and $f_{j2}$ to maximize their profits, $\pi_{j2}$. That is, they solve

$$\max_{f_{j2},x_{j2}} \{pwx_{j2}^{\frac{2}{4}}(f_{j2}-\theta[f_{i1}^R+f_{j1}])^{\frac{1}{4}}-cx_{j2}-zf_{j2}-T\}.$$

$$\text{s.t. } T = \frac{1}{2\delta}[cx_{i1} + c\delta x_{i2} - cx_{j1} - c\delta x_{j2} - \delta pw\sqrt{x_{i2}}\sqrt[4]{f_{i2} - \theta\left(f_{i1}^R + f_{j1}\right)}\sqrt{x_{j1}}$$

$$+\delta pw\sqrt{x_{j2}}\sqrt[4]{f_{j2} - \theta\left(f_{i1}^R + f_{j1}\right)} - pw\sqrt[4]{f_{i1}^R}\sqrt{x_{i1}} + zf_{i1}^R + \delta zf_{i2} - z\left(f_{j1} + \delta f_{j2}\right) + pw\sqrt[4]{f_{j1}}].$$

Therefore, the first-order conditions for $x_{j2}$ and $f_{j2}$ for grower $j$ are

$$\frac{1}{4}\left(\frac{pw\sqrt[4]{f_{j2} - \theta\left(f_{i1}^R + f_{j1}\right)}}{\sqrt{x_{j2}}} - 2c\right) = 0 \text{ and}$$

$$\frac{1}{8}\left(\frac{pw\sqrt{x_{j2}}}{\left(-\theta f_{i1}^R - \theta f_{j1} + f_{j2}\right)^{3/4}} - 4z\right) = 0.$$

Utilizing the above conditions and solving we find

$$\hat{x_{j2}} = \frac{p^4w^4}{32c^3z} \text{ and}$$

$$f_{j2}(f_{i1}^R, f_{j1}) = \theta f_{i1}^R + \theta f_{j1} \pm \frac{p^4w^4}{64c^2z^2}$$

As before, we select the strictly positive values for our analysis. In period 1, grower $j$ chooses $x_{j1}$, $f_{j1}$ and $f_{i1}^R$ to maximize discounted aggregate profits. That is, they solve

$$\max_{x_{j1}, f_{j1}, f_{i1}^R}\{pwx_{j1}^{\frac{2}{4}}f_{j1}^{\frac{1}{4}} - cx_{j1} - zf_{j1} + \delta(pwx_{j2}^{\frac{2}{4}}(f_{j2} - \theta[f_{i1}^R + f_{j1}])^{\frac{1}{4}} - cx_{j2} - zf_{j2} - T)\}.$$

For which the first-order conditions for $x_{j1}$, $f_{j1}$ and $f_{i1}^R$, respectively, are

$$\frac{1}{4}\left(\frac{pw\sqrt[4]{f_{j1}}}{\sqrt{x_{j1}}} - 2c\right) = 0$$

$$\frac{1}{8}\left(\frac{pw\sqrt{x_{j1}}}{(f_{i1}^R)^{3/4}} - 4(2\delta\theta z + z)\right) = 0$$

$$\frac{1}{8}\left(\frac{pw\sqrt{x_{i1}}}{(f_{i1}^R)^{3/4}} - 4(2\delta\theta z + z)\right) = 0.$$

In period 1, grower $i$ solves

$$\max_{x_{i1}}\{pwx_{i1}^{\frac{2}{4}}(f_{i1}^R)^{\frac{1}{4}} - cx_{i1} - zf_{i1}^R + \delta(pwx_{i2}^{\frac{2}{4}}(f_{i2} - \theta[f_{i1}^R + f_{j1}])^{\frac{1}{4}} - cx_{i2} - zf_{i2} + T)\}.$$

For which the first-order condition for $x_{i1}$ is

$$\frac{1}{8}\left(\sqrt[3]{\frac{2}{\frac{z(2\delta\theta+1)x_{i1}}{p^4w^4}}} - 4c\right) = 0.$$

Using the first-order conditions and the previously obtained expressions, we obtain

(i) in period 1:

$$\hat{f}_{i1}^R = \frac{p^4w^4}{64c^2z^2(1+2\delta\theta)^2} \text{ and } \hat{x}_{i1} = \frac{p^4w^4}{32c^3z(1+2\delta\theta)};$$

(ii) in period 2:

$$\hat{f}_{i2} = \frac{p^4w^4\left(1+2\theta[1+2\delta]+4\delta^2\theta^2\right)}{64c^2z^2(1+2\delta\theta)^2} \text{ and } \hat{x}_{i2} = \frac{p^4w^4}{32c^3z}.$$

## A.6 Proof of Corollary 2

The socially optimal levels (seen in Lemma 2) are equivalent to those in Proposition 2.

## A.7 Proof of Lemma 3

The optimal compensation associated with the complete information setting, $\hat{T}$, where

$$\pi_{i1}(x_{i1}, f_{i1}^R) + \delta\pi_{i2}(x_{i2}, f_{i2}, f_{i1}^R, f_{j1}; T) \geq \sum_{t=1}^{2}\pi_{it}^*(\cdot).$$

Evaluating the above condition in equilibrium (evaluating the right-hand side with Proposition 1 with the left-hand side with Proposition 2), we find

$$\hat{T} = \frac{p^4 w^4 \left[\delta\theta\left(\delta\theta\left[2\delta\theta\left(\gamma^{\frac{1}{2}} - 4\right) + 11\gamma^{\frac{1}{2}} - 20\right] + 4\left[3\gamma^{\frac{1}{2}} - 4\right]\right) + 4\left(\gamma^{\frac{1}{2}} - 1\right)\right]}{64\delta z \gamma^{5/2} c^2 (1+\delta\theta)^2},$$

where $\gamma = 1 + 2\delta\theta$. Further, $\hat{T}$ is positive for all admissible parameter values.

## A.8 Proof of Proposition 3

In period 2, because grower $i$ is perfectly informed, their choices coincide with those from Proposition 1. Grower $j$ chooses $x_{j2}$ and $f_{j2}$ to maximize their profits, $\pi_{j2}$.

$$\max_{f_{j2}, x_{j2}} \{pwx_{j2}^{\frac{2}{4}}(f_{j2} - \theta_m[f_{i1} + f_{j1}])^{\frac{1}{4}} - cx_{j2} - zf_{j2}\}.$$

Therefore, the first-order conditions for $x_{j2}$ and $f_{j2}$, respectively, for grower $j$ are

$$\frac{pw\sqrt[4]{f_{j2} - \theta_m\left(f_{i1} + f_{j1}\right)}}{2\sqrt{x_{j2}}} - c = 0$$

$$\frac{pw\sqrt{x_{j2}}}{4\left(f_{j2} - \theta_m\left(f_{i1} + f_{j1}\right)\right)^{3/4}} - z = 0.$$

Utilizing the above conditions and solving for $f_{j2}(f_{i1}, f_{j1})$ yields

$$f_{j2}(f_{i1}, f_{j1}) = \theta_m(f_{i1} + f_{j1}) \pm \frac{p^4 w^4}{64c^2 z^2}.$$

As before, we select the strictly positive values for our analysis. In period 1, grower $i$'s problem coincides with that in Proposition 1. Grower $j$, however, solves

$$\max_{f_{j1}, x_{j1}} \{pwx_{j1}^{\frac{2}{4}} f_{j1}^{\frac{1}{4}} - cx_{j1} - zf_{j1} + \delta(pwx_{j2}^{\frac{2}{4}}(f_{j2} - \theta_m[f_{i1} + f_{j1}])^{\frac{1}{4}} - cx_{j2} - zf_{j2})\}.$$

Therefore, the first-order conditions for $x_{j1}$ and $f_{j1}$, respectively, for grower $j$ are

$$\frac{pw\sqrt[4]{f_{j1}}}{2\sqrt{x_{j1}}} - c = 0$$

$$\frac{pw\sqrt{x_{j1}}}{4f_{j1}^{3/4}} - z\left(\delta\theta_m + 1\right)) = 0.$$

We solve for the optimal levels of fungicide and other inputs in both periods.

(i) in period 1:

$$\bar{f}_{i1} = \frac{p^4w^4}{64c^2z^2(1+\delta\theta)^2} \text{ and } \bar{f}_{j1} = \frac{p^4w^4}{64c^2z^2\left(1+\delta\theta_m\right)^2};$$

$$\bar{x}_{i1} = \frac{p^4w^4}{32c^3z(1+\delta\theta)} \text{ and } \bar{x}_{j1} = \frac{p^4w^4}{32c^3z\left(1+\delta\theta_m\right)};$$

(ii) in period 2:

$$\bar{f}_{i2} = \frac{p^4w^4\left(1+\theta\left[\frac{1}{(1+\delta\theta)^2}+\frac{1}{(1+\delta\theta_m)^2}\right]\right)}{64c^2z^2} \text{ and } \bar{f}_{j2} = \frac{p^4w^4\left(1+\theta_m\left[\frac{1}{(1+\delta\theta)^2}+\frac{1}{(1+\delta\theta_m)^2}\right]\right)}{64c^2z^2};$$

$$\bar{x}_{i2} = \bar{x}_{j2} = \frac{p^4w^4}{32c^3z}.$$

## A.9 Proof of Corollary 3

Grower $j$'s fungicide use in period 1, in the misinformed state without compensation mechanism, compared to the socially optimal choice, depending on the relative level of misinformation to the true severity of fungicide resistance, is

$$\bar{f}_{j1} \gtreqless f_{j1}^{SO}$$

Substituting in the values from their respective propositions, this becomes

$$\frac{p^4 w^4}{64c^2 z^2 \left(1+\delta\theta_m\right)^2} \gtreqless \frac{p^4 w^4}{64c^2 z^2 (1+2\delta\theta)^2}.$$

This implies

$$\theta_m \lesseqgtr 2\theta.$$

## A.10 Proof of Proposition 4

In period 2, grower $i$ chooses $x_{i2}$ to maximize their profits, $\pi_{i2}$. That is, they solve

$$\max_{x_{i2}, f_{i2}} \{pwx_{i2}^{\frac{2}{4}}(f_{i2} - \theta[f_{i1}^R + f_{j1}])^{\frac{1}{4}} - cx_{i2} - zf_{i2} + T\}$$

$$\text{s.t. } \pi_{i1}(x_{i1}, f_{i1}^R) + \delta\pi_{i2}(x_{i2}, f_{i2}, f_{i1}^R, f_{j1}; T) + \pi_{j1}(x_{j1}, f_{j1}) + \delta\pi_{j2}(x_{j2}, f_{j2}, f_{i1}^R, f_{j1}; T)$$
$$= \sum_{t=1}^{2} \pi_{it}^*(\cdot) + \pi_{jt}^*(\cdot)$$

Therefore, $T$ is

$$T = \frac{1}{2\delta}[cx_{i1} - \delta pw\sqrt{x_{i2}}\sqrt[4]{f_{i2} - \theta\left(f_{i1}^R + f_{j1}\right)} - pw\sqrt[4]{f_{i1}^R}\sqrt{x_{i1}} + zf_{i1} + \delta zf_{i2} - z\left(f_{j1} + \delta f_{j2}\right)$$

$$+c\delta x_{i2} - cx_{j1} - c\delta x_{j2} + \delta pw\sqrt{x_{j2}}\sqrt[4]{f_{j2} - \theta_m\left(f_{i1}^R + f_{j1}\right)} + pw\sqrt[4]{f_{j1}}\sqrt{x_{j1}}]$$

The first-order conditions for $x_{i2}$ and $f_{i2}$, respectively, for grower $i$ are

$$\frac{1}{4}\left(\frac{pw\sqrt[4]{f_{i2} - \theta\left(f_{i1}^R + f_{j1}\right)}}{\sqrt{x_{i2}}} - 2c\right) = 0$$

$$\frac{1}{8}\left(\frac{pw\sqrt{x_{i2}}}{\left(f_{i2} - \theta\left(f_{i1}^R + f_{j1}\right)\right)^{3/4}} - 4z\right) = 0.$$

Using the above conditions we obtain

$$\hat{x}_{i2} = \frac{p^4 w^4}{32c^3 z} \text{ and } f_{i2}(f_{i1}^R, f_{j1}) = \theta(f_{i1}^R + f_{j1}) \pm \frac{p^4 w^4}{64c^2 z^2}.$$

We select the strictly positive values for our analysis. In period 2, grower $j$ solves

$$\max_{f_{j2}, x_{j2}} \{pwx_{j2}^{\frac{2}{4}}(f_{j2} - \theta_m[f_{i1}^R + f_{j1}])^{\frac{1}{4}} - cx_{j2} - zf_{j2} - T\}$$

$$\text{s.t. } T = \frac{1}{2\delta}[cx_{i1} - \delta pw\sqrt{x_{i2}}\sqrt[4]{f_{i2} - \theta\left(f_{i1} + f_{j1}\right)} - pw\sqrt[4]{f_{i1}^R}\sqrt{x_{i1}} + zf_{i1} + \delta zf_{i2} - z\left(f_{j1} + \delta f_{j2}\right)$$
$$+c\delta x_{i2} - cx_{j1} - c\delta x_{j2} + \delta pw\sqrt{x_{j2}}\sqrt[4]{f_{j2} - \theta_m\left(f_{i1}^R + f_{j1}\right)} + pw\sqrt[4]{f_{i1}^R}\sqrt{x_{j1}}].$$

Therefore, the first-order conditions for $x_{j2}$ and $f_{j2}$ for grower $j$ are

$$\frac{1}{4}\left(\frac{pw\sqrt[4]{f_{j2} - \theta_m\left(f_{i1}^R + f_{j1}\right)}}{\sqrt{x_{j2}}} - 2c\right) = 0 \text{ and}$$

$$\frac{1}{8}\left(\frac{pw\sqrt{x_{j2}}}{\left(f_{j2} - \theta_m\left(f_{i1}^R + f_{j1}\right)\right)^{3/4}} - 4z\right) = 0.$$

Utilizing the above conditions and solving we find

$$\hat{x_{j2}} = \frac{p^4 w^4}{32c^3 z} \text{ and}$$

$$f_{j2}(f_{i1}^R, f_{j1}) = \theta_m(f_{i1}^R + f_{j1}) \pm \frac{p^4 w^4}{64c^2 z^2}$$

As before, we select the strictly positive values for our analysis. In period 1, grower $j$ solves

$$\max_{x_{j1}, f_{j1}, f_{i1}^R} \{pwx_{j1}^{\frac{2}{4}} f_{j1}^{\frac{1}{4}} - cx_{j1} - zf_{j1} + \delta(pwx_{j2}^{\frac{2}{4}}(f_{j2} - \theta_m[f_{i1}^R + f_{j1}])^{\frac{1}{4}} - cx_{j2} - zf_{j2} - T)\}.$$

For which the first-order conditions for $x_{j1}$, $f_{j1}$ and $f^R_{i1}$, respectively, are

$$\frac{1}{4}\left(\frac{pw\sqrt[4]{f_{j1}}}{\sqrt{x_{j1}}}-2c\right)=0$$

$$\frac{1}{8}\left(\frac{pw\sqrt{x_{j1}}}{f_{j1}^{3/4}}-4z\left(\delta\theta+\delta\theta_m+1\right)\right)=0$$

$$\frac{1}{8}\left(\frac{pw\sqrt{x_{i1}}}{(f^R_{i1})^{3/4}}-4z\left(\delta\theta+\delta\theta_m+1\right)\right)=0.$$

In period 1, grower $i$ solves

$$\max_{x_{i1}}\{pwx_{i1}^{\frac{2}{4}}(f^R_{i1})^{\frac{1}{4}}-cx_{i1}-zf^R_{i1}+\delta(pwx_{i2}^{\frac{2}{4}}(f_{i2}-\theta[f^R_{i1}+f_{j1}])^{\frac{1}{4}}-cx_{i2}-zf_{i2}+T)\}.$$

For which the first-order condition for $x_{i1}$ is

$$\frac{1}{8}\left(\frac{\sqrt[3]{2}pw}{\sqrt[3]{\frac{zx_{i1}(\delta\theta+\delta\theta_m+1)}{pw}}}-4c\right)=0.$$

Using the first-order conditions and the previously obtained expressions, we obtain

(i) in period 1:

$$\widetilde{f}^R_{i1}=\widetilde{f}_{j1}=\frac{p^4w^4}{64c^2z^2\left(1+\delta[\theta+\theta_m]\right)^2};$$

$$\widetilde{x}_{i1}=\widetilde{x}_{j1}=\frac{p^4w^4}{32c^3z\left(1+\delta[\theta+\theta_m]\right)};$$

(ii) in period 2:

$$\widetilde{f}_{i2}=\frac{p^4w^4\left(\frac{2\theta}{[1+\delta(\theta+\theta_m)]^2}+1\right)}{64c^2z^2}\text{ and }\widetilde{f}_{j2}=\frac{p^4w^4\left(\frac{2\theta_m}{[1+\delta(\theta+\theta_m)]^2}+1\right)}{64c^2z^2};$$

$$\widetilde{x}_{i2}=\widetilde{x}_{j2}=\frac{p^4w^4}{32c^3z};$$

## A.11 Proof of Lemma 4

The optimal compensation associated with the setting where grower $j$ is misinformed, $\widetilde{T}$, where

$$\pi_{i1}(x_{i1}, f_{i1}^R) + \delta\pi_{i2}(x_{i2}, f_{i2}, f_{i1}^R, f_{j1}; T) \geq \sum_{t=1}^{2} \overline{\pi}_{it}(\cdot).$$

Evaluating the above condition in equilibrium (evaluating the right-hand side with Proposition 3 with the left-hand side with Proposition 4), we find

$$\widetilde{T} = \frac{\delta p^4 w^4 \left(\theta_m^2 \left[\delta^2\theta_m^2 + 2\delta\theta_m + 1\right] - 2\delta\theta^2\theta_m \left[1 + \delta\theta\right] - \theta^2 \left[\delta^2\theta^2 + 3\delta\theta + 2\right]\right)}{64c^2 z(1 + \delta\theta) \left(1 + \delta\theta_m\right)^2 \left(1 + \delta\theta + \delta\theta_m\right)^2}.$$

To determine when $\widetilde{T}$ is positive, we focus on its numerator because its denominator is strictly positive for all admissible parameter values. For tractability, we assume that $p = w = \delta = 1$ and consider three possible cases for fungicide resistance severity (mild resistance, $\theta = \frac{1}{4}$, intermediate resistance, $\theta = \frac{1}{2}$, and severe resistance, $\theta = \frac{3}{4}$, respectively). For each case, we determine which values of fungicide resistance misinformation, $\theta_m$, allow for compensation to be positive. When fungicide resistance is mild, $\theta = \frac{1}{4}$, it must be that

$$\theta_m^4 + 2\theta_m^3 + \theta_m^2 - \frac{5\theta_m}{32} - \frac{45}{256} > 0,$$

which requires that $\theta_m \gtrapprox 0.3549$. When fungicide resistance severity is intermediate, $\theta = \frac{1}{2}$, compensation is only positive if

$$\theta_m^4 + 2\theta_m^3 + \theta_m^2 - \frac{3\theta_m}{4} - \frac{15}{16} > 0,$$

$\theta_m \gtrapprox 0.7092$. Finally, if fungicide resistance is severe, $\theta = \frac{3}{4}$, it necessitates

$$\theta_m^4 + 2\theta_m^3 + \theta_m^2 - \frac{63\theta_m}{32} - \frac{693}{256} > 0,$$

which cannot be satisfied for any admissible $\theta_m$. Therefore, no admissible misinformed fungicide severity allows for $\widetilde{T} > 0$ when $\theta = \frac{3}{4}$.

## A.12 Proof of Corollary 4

Grower $j$'s fungicide use in period 1, in the misinformed state with the compensation mechanism, compared to the socially optimal choice is

$$\widetilde{f}_{j1} \gtreqless f_{j1}^{SO}$$

Substituting in the values from their respective propositions, this becomes

$$\frac{p^4 w^4}{64c^2 z^2 \left(1 + \delta[\theta + \theta_m]\right)^2} \gtreqless \frac{p^4 w^4}{64c^2 z^2 (1 + 2\delta\theta)^2}$$

$$\theta + \theta_m \lesseqgtr 2\theta$$

$$\theta_m \lesseqgtr \theta$$

## A.13 Proof of Proposition 5

In period 2, grower $i$ solves

$$\max_{x_{i2}, f_{i2}} \{pwx_{i2}^{\frac{2}{4}}(f_{i2} - \theta_m[f_{i1}^R + f_{j1}])^{\frac{1}{4}} - cx_{i2} - zf_{i2} + T\}$$

$$\text{s.t. } \pi_{i1}(x_{i1}, f_{i1}^R) + \delta\pi_{i2}(x_{i2}, f_{i2}, f_{i1}^R, f_{j1}; T) + \pi_{j1}(x_{j1}, f_{j1}) + \delta\pi_{j2}(x_{j2}, f_{j2}, f_{i1}^R, f_{j1}; T) = \sum_{t=1}^{2} \pi_{it}^*(\cdot) + \pi_{jt}^*(\cdot).$$

Therefore, $T$ is

$$T=\frac{1}{2\delta}[cx_{i1}+c\delta x_{i2}-cx_{j1}-c\delta x_{j2}-\delta pw\sqrt{x_{i2}}\sqrt[4]{f_{i2}-\theta_m\left(f_{i1}^R+f_{j1}\right)}$$

$$+\delta pw\sqrt{x_{j2}}\sqrt[4]{f_{j2}-\theta\left(f_{i1}^R+f_{j1}\right)}-pw\sqrt[4]{f_{i1}^R}\sqrt{x_{i1}}+zf_{i1}^R+\delta zf_{i2}$$

$$+pw\sqrt[4]{f_{j1}}\sqrt{x_{j1}}-zf_{j1}-\delta zf_{j2}].$$

The corresponding first-order conditions for $x_{i2}$ and $f_{i2}$, respectively, for grower $i$ are

$$\frac{1}{4}\left(\frac{pw\sqrt[4]{f_{i2}-\theta_m\left(f_{i1}^R+f_{j1}\right)}}{\sqrt{x_{i2}}}-2c\right)=0$$

$$\frac{1}{8}\left(\frac{pw\sqrt{x_{i2}}}{\left(f_{i2}-\theta_m\left(f_{i1}^R+f_{j1}\right)\right)^{3/4}}-4z\right)=0.$$

Using the above conditions we obtain

$$\hat{x}_{i2}=\frac{p^4w^4}{32c^3z}\text{ and }f_{i2}(f_{i1}^R,f_{j1})=\theta_m(f_{i1}^R+f_{j1})\pm\frac{p^4w^4}{64c^2z^2}$$

We select the strictly positive values for our analysis. In period 2, grower $j$ solves

$$\max_{f_{j2},x_{j2}}\{pwx_{j2}^{\frac{2}{4}}(f_{j2}-\theta[f_{i1}^R+f_{j1}])^{\frac{1}{4}}-cx_{j2}-zf_{j2}-T\}.$$

$$\text{s.t. }T=\frac{1}{2\delta}[cx_{i1}+c\delta x_{i2}-cx_{j1}-c\delta x_{j2}-\delta pw\sqrt{x_{i2}}\sqrt[4]{f_{i2}-\theta_m\left(f_{i1}^R+f_{j1}\right)}$$

$$+\delta pw\sqrt{x_{j2}}\sqrt[4]{f_{j2}-\theta\left(f_{i1}^R+f_{j1}\right)}-pw\sqrt[4]{f_{i1}^R}\sqrt{x_{i1}}+zf_{i1}^R+\delta zf_{i2}$$

$$+pw\sqrt[4]{f_{j1}}\sqrt{x_{j1}}-zf_{j1}-\delta zf_{j2}].$$

Therefore, the first-order conditions for $x_{j2}$ and $f_{j2}$ for grower $j$ are

$$\frac{1}{4}\left(\frac{pw\sqrt[4]{f_{j2}-\theta\left(f_{i1}^{R}+f_{j1}\right)}}{\sqrt{x_{j2}}}-2c\right)=0 \text{ and}$$

$$\frac{1}{8}\left(\frac{pw\sqrt{x_{j2}}}{\left(-\theta f_{i1}^{R}-\theta f_{j1}+f_{j2}\right)^{3/4}}-4z\right)=0.$$

Utilizing the above conditions and solving we find

$$\hat{x_{j2}}=\frac{p^4w^4}{32c^3z} \text{ and}$$

$$f_{j2}(f_{i1}^{R},f_{j1})=\theta(f_{i1}^{R}+f_{j1})\pm\frac{p^4w^4}{64c^2z^2}.$$

As before, we select the strictly positive values for our analysis. In period 1, grower $j$ solves

$$\max_{x_{j1},f_{j1},f_{i1}}\{pwx_{j1}^{\frac{2}{4}}f_{j1}^{\frac{1}{4}}-cx_{j1}-zf_{j1}+\delta(pwx_{j2}^{\frac{2}{4}}(f_{j2}-\theta[f_{i1}^{R}+f_{j1}])^{\frac{1}{4}}-cx_{j2}-zf_{j2}-T)\}.$$

For which the first-order conditions for $x_{j1}$, $f_{j1}$ and $f_{i1}^{R}$, respectively, are

$$\frac{1}{4}\left(\frac{pw\sqrt[4]{f_{j1}}}{\sqrt{x_{j1}}}-2c\right)=0,$$

$$\frac{1}{8}\left(\frac{pw\sqrt{x_{j1}}}{f_{j1}^{3/4}}-4z\left(3\delta\theta-\delta\theta_m+1\right)\right)=0 \text{ and}$$

$$\frac{1}{8}\left(\frac{pw\sqrt{x_{i1}}}{(f_{i1}^{R})^{3/4}}-4z\left(3\delta\theta-\delta\theta_m+1\right)\right)=0.$$

In period 1, grower $i$ solves

$$\max_{x_{i1}}\{pwx_{i1}^{\frac{2}{4}}(f_{i1}^{R})^{\frac{1}{4}}-cx_{i1}-zf_{i1}^{R}+\delta(pwx_{i2}^{\frac{2}{4}}(f_{i2}-\theta_m[f_{i1}^{R}+f_{j1}])^{\frac{1}{4}}-cx_{i2}-zf_{i2}+T)\}.$$

For which the first-order condition for $x_{i1}$ is

$$\frac{1}{24}\left(-12c+\frac{4\sqrt[3]{2}(pw)^{4/3}\sqrt[4]{\frac{1}{(z(3\delta\theta-\delta\theta_m+1))^{4/3}}}}{\sqrt[3]{x_{i1}}}+\frac{\sqrt[3]{2}(pw)^{4/3}\left(\delta\theta-3\delta\theta_m-1\right)}{\sqrt[3]{zx_{i1}}\left(3\delta\theta-\delta\theta_m+1\right)^{4/3}}\right)=0.$$

The equilibrium results are

(i) in period 1:

$$\check{f}_{i1}^R=\frac{p^4w^4\left(13\delta\theta-7\delta\theta_m+3\right)^2}{576c^2z^2\left(\delta[3\theta-\theta_m]+1\right)^4}\text{ and }\check{f}_{j1}=\frac{p^4w^4}{64c^2z^2\left(\delta[3\theta-\theta_m]+1\right)^2};$$

$$\check{x}_{i1}=\frac{p^4w^4\left(13\delta\theta-7\delta\theta_m+3\right)^3}{864c^3z\left(\delta[3\theta-\theta_m]+1\right)^4}\text{ and }\check{x}_{j1}=\frac{p^4w^4}{32c^3z\sqrt{(\delta[3\theta-\theta_m]+1)^2}};$$

(ii) in period 2:

$$\check{f}_{i2}=\theta_m\check{f}_{i1}^R+\frac{9p^4w^4}{576c^2z^2}\left(\frac{\theta_m+[\delta(3\theta-\theta_m)+1]^2}{[\delta(3\theta-\theta_m)+1]^2}\right)\text{ and}$$

$$\check{f}_{j2}=\theta\check{f}_{i1}^R+\frac{9p^4w^4}{576c^2z^2}\left(\frac{\theta+[\delta(3\theta-\theta_m)+1]^2}{[\delta(3\theta-\theta_m)+1]^2}\right);$$

$$\check{x}_{i2}=\check{x}_{j2}=\frac{p^4w^4}{32c^3z};$$

where input levels in both periods are strictly positive for any nonnegative price.

Note here that we consider that the relationship between the misinformed fungicide resistance severity and the true severity is such that the first-period equilibrium fungicide level for grower $i$ is nonzero (we simplify the value assuming: $0<\theta_m<\frac{13\delta\theta+3}{7\delta}$). If we were to relax this assumption, it would complicate the comparisons. The optimal compensation associated with the setting where grower $i$ is misinformed, $\check{T}$, where

$$\pi_{i1}(x_{i1},f_{i1}^R)+\delta\pi_{i2}(x_{i2},f_{i2},f_{i1}^R,f_{j1};T)\geq\sum_{t=1}^{2}\overline{\pi}_{it}(\cdot).$$

Evaluating the above condition in equilibrium, we obtain

$$\check{T} = \frac{1}{1728}[648 - \frac{16m(-13\theta+7m-3)^3}{(-3\theta+m-1)^4} + \frac{216m}{(-3\theta+m-1)^2}) + \frac{24(13\theta-7m+3)^2}{(-3\theta+m-1)^4}$$

$$+\frac{16(13\theta-7m+3)^3}{(-3\theta+m-1)^4} + 216\left(\frac{1}{\theta+1} - \frac{\theta}{(m+1)^2} + 1\right)$$

$$-\frac{96\sqrt{(13\theta-7m+3)^3}\sqrt{|-7m+13\theta+3|}}{(-3\theta+m-1)^2\,|-m+3\theta+1|}$$

$$-\frac{288\sqrt[4]{3}\sqrt[4]{27(-3\theta+m-1)^4+27m(-3\theta+m-1)^2-27\theta(-3\theta+m-1)^2+2m(13\theta-7m+3)^3-3\theta(13\theta-7m+3)^2}}{|-m+3\theta+1|}$$

## A.14 Proof of Corollary 6

For both subsections 3.1 and 3.2, we consider two illustrative cases ($p = 1, w = 1, c = \frac{1}{2}, z = \frac{1}{2}, \delta = 1, \theta = \frac{1}{4}$ and $p = 1, w = 1, c = \frac{1}{2}, z = \frac{1}{2}, \delta = 1, \theta = \frac{3}{4}$, respectively).

**Compensating Grower $j$ is Misinformed**

To begin, we demonstrate that in Subsection 3.1 (where the compensating grower $j$ is misinformed) social welfare is greater in the social planner's problem than in the case with the compensation mechanism in Subsection 3.1.

The difference between social welfare in the social planner's problem and social welfare in this case with the misinformed compensating grower $j$ is

$$\frac{p^4w^4\left(2\delta^2\theta+\delta+1\right)}{32c^2(2\delta\theta z+z)} + \frac{p^4w^4\left(\delta^2\theta+\delta+\delta^2\theta_m-1\right)}{32c^2z\left(\delta\theta+\delta\theta_m+1\right)}$$

$$-\frac{p^4w^4\left(2\delta\sqrt{\delta\theta+\delta\theta_m+1}\sqrt[4]{\delta^2\theta^2+2(\delta-1)\theta+\delta^2\theta_m^2+2\left(\delta^2\theta+\delta+1\right)\theta_m+1}\right)}{32c^2z\left(\delta\theta+\delta\theta_m+1\right)}$$

**Case 1, Mild Fungicide Resistance**

Next, we substitute in the parameter values we associate with mild fungicide resistance

$(p = 1, w = 1, c = \frac{1}{2}, z = \frac{1}{2}, \delta = 1, \theta = \frac{1}{4})$. The difference becomes

$$\frac{14 - 3(16\theta_m^2 + 72\theta_m + 17)^{\frac{1}{4}}(4\theta_m + 5)^{\frac{1}{2}} + 16\theta_m}{24\theta_m + 30}$$

The above difference is only equal to zero when $\theta_m = \frac{1}{4}$. That is, social welfare only coincides in the two scenarios when grower $j$ is not misinformed. The above expression, however, is positive for all admissible parameter values.

**Case 2, Severe Fungicide Resistance**

Next, we substitute in the parameter values we associate with severe fungicide resistance $(p = 1, w = 1, c = \frac{1}{2}, z = \frac{1}{2}, \delta = 1, \theta = \frac{3}{4})$. The difference becomes

$$\frac{32 - 5(4\theta_m + 7)^{\frac{1}{2}}(8\theta_m[2\theta_m + 11] + 25)^{\frac{1}{4}} + 24\theta_m}{40\theta_m + 70}$$

The above difference is only equal to zero when $\theta_m = \frac{3}{4}$. That is, social welfare only coincides in the two scenarios when grower $j$ is not misinformed. The above expression, however, is positive for all admissible parameter values.

### Compensating Grower $i$ is Misinformed

We use the following figure to illustrate the cases for when grower $i$, the compensated grower, is misinformed.

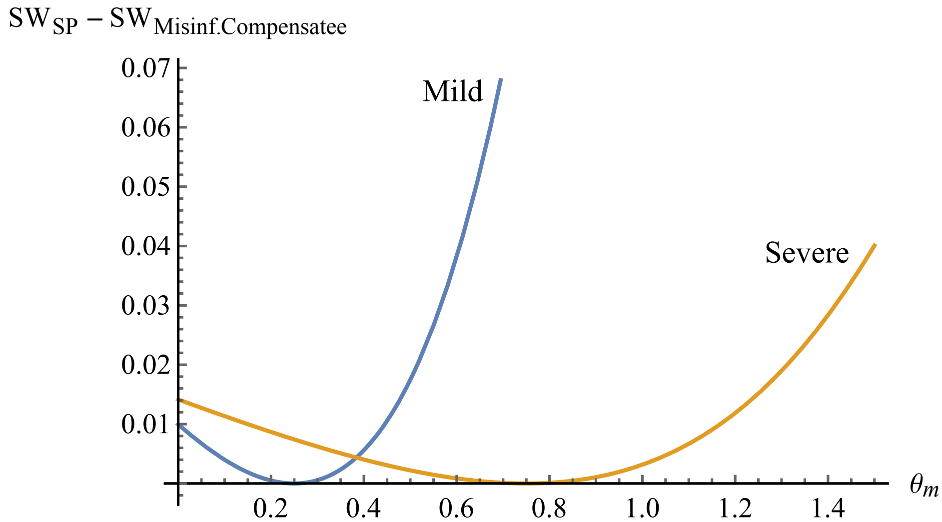


Figure 5: Severe fungicide resistance with misinformed grower $i$.

We find that, similar to when grower $j$ is misinformed, social welfare in both cases only coincides with that when the social planner determines inputs when grower $i$ is not misinformed.

## A.15 Additional Figures

In each of the figures included in this section, lowering the marginal cost of fungicide or all other inputs, respectively, decreases the differences between alternate scenarios as misinformation gets more extreme. That is, with lower marginal costs, the social welfare gaps across scenarios diminish somewhat.

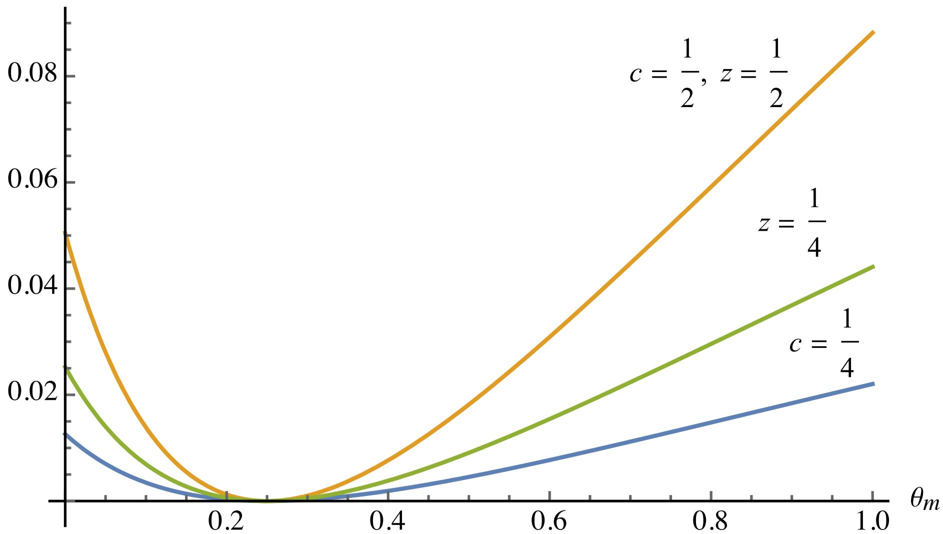


Figure 6: $SW_{SP} - SW_{Misinf.Compensator}$, Alt. Parameter Values from Figure 3.

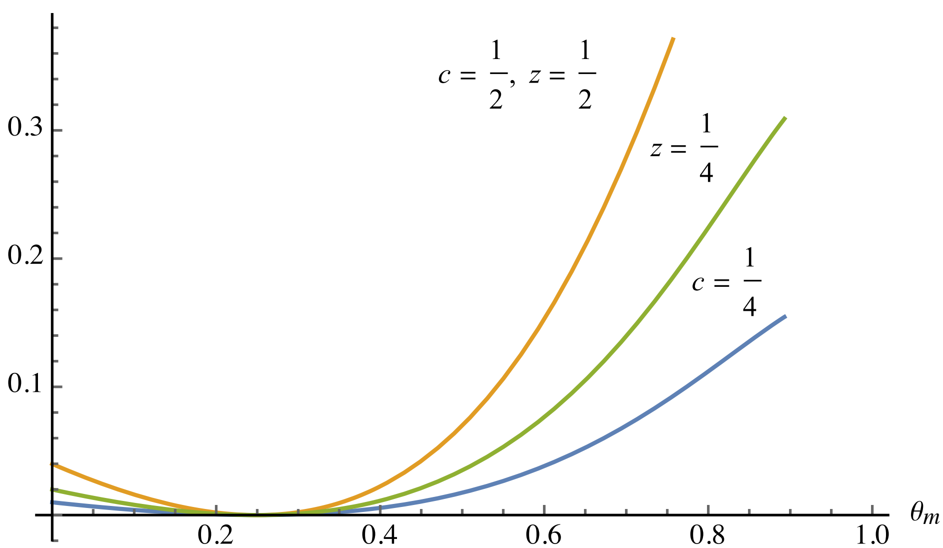


Figure 7: $SW_{SP} - SW_{Misinf.Compensatee}$, Alt. Parameter Values from Figure 3.

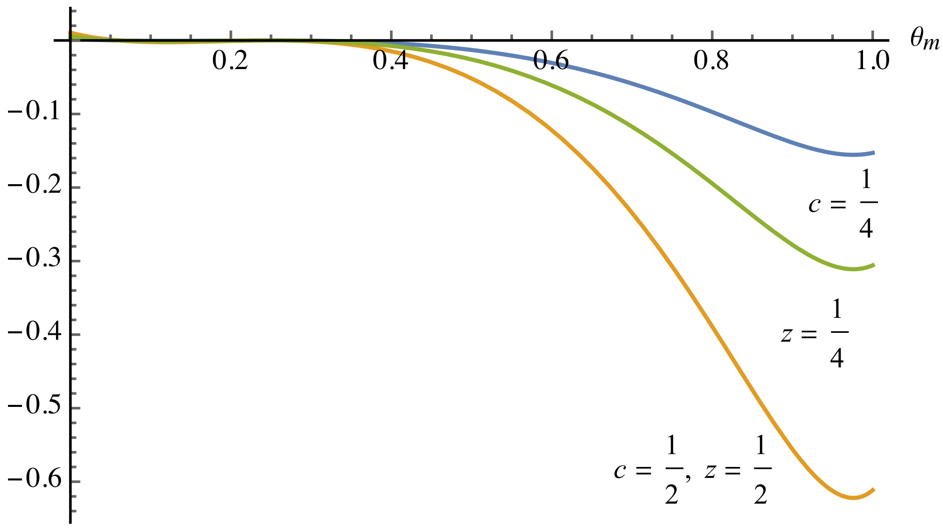


Figure 8: Mild, Alt. Parameter Values from Figure 4.

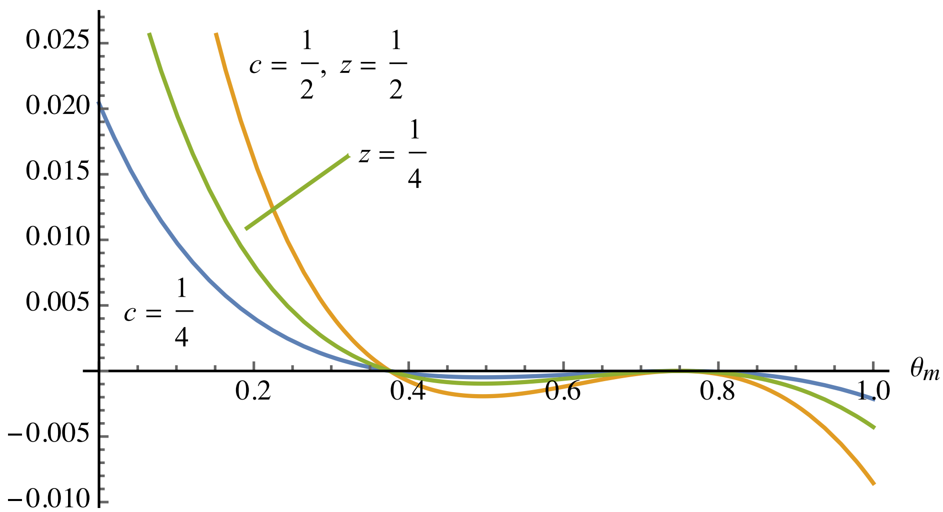


Figure 9: Severe, Alt. Parameter Values from Figure 4.