# Fungicide Resistance and Misinformation: A Game Theoretic Approach*

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**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 ameliorates pesticide 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. In particular, we find that if a misinformed grower holds pessimistic beliefs, transfers can be excessively high. Similarly, if all growers are misinformed and they hold very asymmetric beliefs, transfers are higher than a context of complete information.

*Keywords*: Fungicide resistance, game theory, compensation mechanism, intertemporal externality, misinformation.

*JEL Codes*: $C73$, $D21$, $H23$, $Q16$

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# 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 understanding 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 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 promotes cooperation among growers and provides a monetary transfer between growers when they experience a profit loss from participating. In addition, it can be used in a more general context of pesticide resistance where farmers' usage of pesticide affects the pesticide effectiveness, i.e., a negative intertemporal production externality is present. Our approach 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) develop a self-enforcing cooperative agreement with variable transfer payments to control, as an example, a mammal population. Liu and Sims (2016) use a side payment to incentivize producers to coordinate control of transboundary species invasions in a spatial-dynamic control model. Sims et al. (2018) determine the optimal timing of risk-reduction strategies for addressing problems of ecological change, using bioinvasion as an

[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. When the subsidy is not revenue neutral, the cost is borne by the society; the compensation mechanism we consider involves a monetary agreement between the growers only.

[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.

example, and discuss 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 under certain conditions pesticide manufacturers have incentives to share information about the likelihood of future 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

[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)).

resistance mitigation efforts when 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 pesticides 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 or both of the growers incorrectly assess the severity of fungicide resistance (one-sided or two-sided misinformation). 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 growers are misinformed about the severity of fungicide resistance, we evaluate the distortions generated by misinformation.

Under complete information, we find that the compensation mechanism drives fungicide usage to the socially optimal level, internalizing the intertemporal externality. However, participation in the mechanism becomes more difficult when we allow for misinformation. In fact, the optimal transfer needs to become more generous when the fungicide resistance

[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.

severity increases. 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 growers could also improve the acceptance of the compensation mechanism.

Given that the compensation mechanism requires the reduction of fungicide usage and a monetary transfer, misinformation about fungicide resistance severity could be detrimental to its performance. As previously mentioned, we consider two contexts of misinformation about the severity of fungicide resistance: (i) one grower is misinformed while the other is completely informed (one-sided misinformation) and (ii) both growers are misinformed (two-sided misinformation). We find that one-sided misinformation generates distortions on the setting of optimal transfers. In particular, if the misinformed grower is incorrectly pessimistic about the severity of fungicide resistance,[10] then the transfer that induces socially optimal fungicide levels is higher than that under complete information. That is, the compensation mechanism relies on an excessively high transfer due to misinformation. However, if the misinformed grower wrongly believes that fungicide resistance severity is very mild (i.e., has optimistic misinformation), the compensation mechanism calls for the misinformed grower to receive compensation paid by the informed grower. In this context, misinformation dictates the role of growers in the mechanism. Hence, participation in the compensation mechanism is achieved if the wrongly optimistic farmer receives the transfer.

In the setting in which both growers are misinformed, we find that the optimal transfer is higher than that under complete information if the compensating grower has sufficiently pessimistic misinformation about fungicide resistance severity while the other grower holds optimistic beliefs. If the difference between growers' beliefs about fungicide resistance sever-

[10]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.

ity is substantial (highly asymmetric misinformation), the transfer required to induce a reduction in fungicide levels is considerably higher than that under a complete information setting. This result suggests that, when growers sustain asymmetric beliefs about fungicide resistance severity, transfers that internalize the externality become more expensive, making growers participation in this mechanism more difficult to achieve. Therefore, accessible educational programs that help advance growers' knowledge about fungicide resistance severity are crucial for the full participation of growers in this mechanism.[11]

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 every grower $i$. Specifically, the production functions for grower $i$ in periods 1 and 2, respectively, are

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

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

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

where $w \in [0, \infty)$ is a weather index parameter; a higher value of $w$ indicates that conditions are more favorable to production.[12] 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 sensitivity of fungicide effectiveness in period 2 to aggregate fungicide levels chosen in period 1 is determined by a fungicide-resistance severity parameter, $\theta \in (0, 1)$. 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. Hence, higher applications of fungicide in period 1 do not necessarily lead to substantially more resistance, it depends on the sensitivity parameter, $\theta$. Finally, $\alpha$ and $\beta$ are the output elasticities for each input, 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.[13] 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

$$C_{it}(x_{it}, f_{it}) \equiv c x_{it} + z f_{it}, \tag{3}$$

where the first term represents the cost of all inputs other than fungicide (with marginal cost $c > 0$) and the second term is the cost of applying fungicide (with marginal cost $z > 0$).

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

[13] Babcock et al. (1992) and Sexton et al. (2007)) discuss the pros and cons of using a Cobb-Douglas production function instead of a damage control framework. For instance, the latter helps to ameliorate overestimation of fungicide productivity while the former avoids the problem of specifying a damage function. Our specification seeks to emphasize the interaction between growers, allowing for the consideration of other inputs, and we do not focus on estimating fungicide productivity.

We do not impose any condition between $c$ and $z$ (i.e., allowing for $c > z$, $c < z$ or $c = z$). 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 output price, $p > 0$ is given.[14] Note that in the first period growers do not face the future consequences of their fungicide. In the second period, the profits for grower $i$ are

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

which are negatively affected by the fungicide choices of both growers in the previous period. We consider that profits in stage 2 are discounted by $\delta \in (0, 1]$. 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

As a benchmark, we first examine the two-stage game without compensation. Profits for periods 1 and 2 correspond with equations (4) and (5), respectively. For simplicity, for the remainder of our analysis we assume that $\alpha = \frac{1}{2}$ and $\beta = \frac{1}{4}$, which facilitates the provision

[14] Seccia et al. (2015) discuss that the global market for table grapes has generally become more competitive over the years. 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.

of meaningful results. The model in Section 2.2 becomes intractable if we allow for general values of these parameters. We include a sensitivity analysis in Appendix A.10 demonstrating that the results are not qualitatively affected if we consider different values for $\alpha$ and $\beta$ as long as output is less sensitive to fungicide use than to all other inputs combined, $\alpha > \beta$ and that the production function satisfies decreasing returns to scale, $\alpha + \beta < 1$.[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. 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. As shown in the proof of Proposition 1, 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,

[15] Grape production is more sensitive to all of the other inputs in conjunction than to fungicide alone.

it manifests as a negative production externality which requires increased applications of fungicide in the period where the externality is present.

We seek to analyze how different equilibrium fungicide use is from socially optimal 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. To focus our analysis on the intertemporal externality, we define social welfare as the sum of growers' profits. Considering environmental damage, e.g., environmental pollution through overuse, represents an extra cost that generates more demanding input levels. In the next lemma, we present the optimal input levels associated with the social planner's problem and compare them to the equilibrium fungicide levels without the compensation mechanism (Proposition 1).

LEMMA 1. *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:*

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

*Therefore, for all admissible parameter values, equilibrium fungicide levels in Proposition 1 are socially excessive.*

This relationship between the equilibrium levels in the game without compensation and the socially optimal levels is 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, as the other effect is taken care of by each grower. That is, because the social planner considers both growers' discounted profits in her maximization, she internalizes the effects of fungicide resistance and responds by reducing inputs in both periods. Regarding other inputs, we observe that $x_{i1}^{SO}$ is lower than in Proposition 1. However, it coincides in the second period. 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 section, we consider that growers $i$ and $j$ enter an agreement where grower $i$ limits his fungicide levels in the first period, which helps to mitigate the fungicide resistance severity experienced in period 2. Given that grower $i$ cannot freely choose his own fungicide level in period 1, the agreement requires grower $j$ to compensate grower $i$ in period 2.[16] This is rooted in a Coasian approach, where the affected parties reach an agreement to address the two-sided externality of fungicide resistance. The incentive mechanism to reduce fungicide is the compensation provided by grower $j$ to grower $i$ for the profit loss associated with reducing fungicide use.

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 next examine the condition that must hold 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,

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

[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).

where $\pi^*_{it}(\cdot)$ is the profit level for grower $i$ in the game without compensation mechanism (from Proposition 1) and $f^R_{i1}$ 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, $f^R_{i1}$ , and makes the transfer, $T$, to grower $i$ is

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

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

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

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

We solve by backward induction and the results of this case are presented in the following proposition.

Proposition 2. *The compensation mechanism induces the socially optimal input levels found in Lemma 1 with transfer*

$$T^{CI} = \frac{\delta\theta^2 p^4 w^4}{64c^2 z(1+\delta\theta)^2(1+2\delta\theta)},$$

*which is positive for all admissible parameter values.*

The optimal transfer induces growers to internalize the intertemporal externality, which in turn leads them to choose the socially optimal input levels. In addition, the transfer decreases in the marginal cost of fungicide, $z$, and increases in fungicide resistance severity, $\theta$. In the next section, we consider that grower $j$ is misinformed about the severity of fungicide resistance (one-sided misinformation) and we also examine a context in which both growers are misinformed (two-sided misinformation).

# 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; as reported for US grape growers by Oliver et al. (2021). 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.

## 3.1 One-Sided Misinformation

We consider first that grower $i$ knows the true severity of fungicide resistance, but grower $j$ is misinformed. This situation can occur if, for instance, grower $i$, but not grower $j$, is experienced or has access to expert crop consultants. That is, rather than knowing the true 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 with and without 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:*

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

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

*where input levels in both periods are strictly positive.*

Similar to the previous section, grower $i$'s choice of fungicide level in equilibrium 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 the socially optimal levels. The following corollary explicitly compares these fungicide levels.

Corollary 1. *Without compensation, the grower $j$'s use of fungicide in period 1 is socially insufficient if and only if $\theta_m > 2\theta$ and coincides with the socially optimal level when $\theta_m = 2\theta$.*

Intuitively, 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 optimum (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 $B$). Finally, 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).[17] In this specific scenario, the misinformation would inadvertently lead the misinformed grower to select the socially optimal outcome, making the compensation mechanism unnecessary.

[17]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.

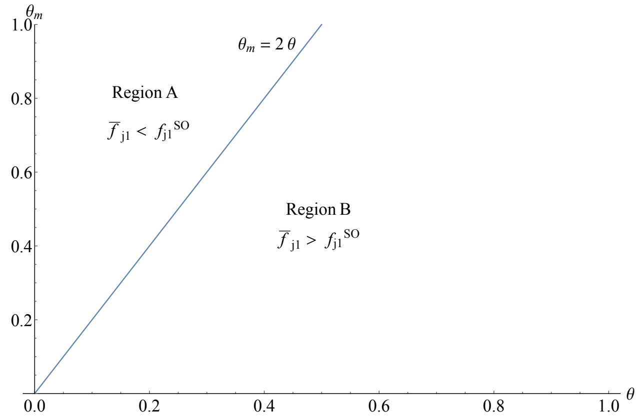



Figure 1: Grower $j$ is misinformed.

In the following proposition, we present the optimal transfer when one grower is misinformed.

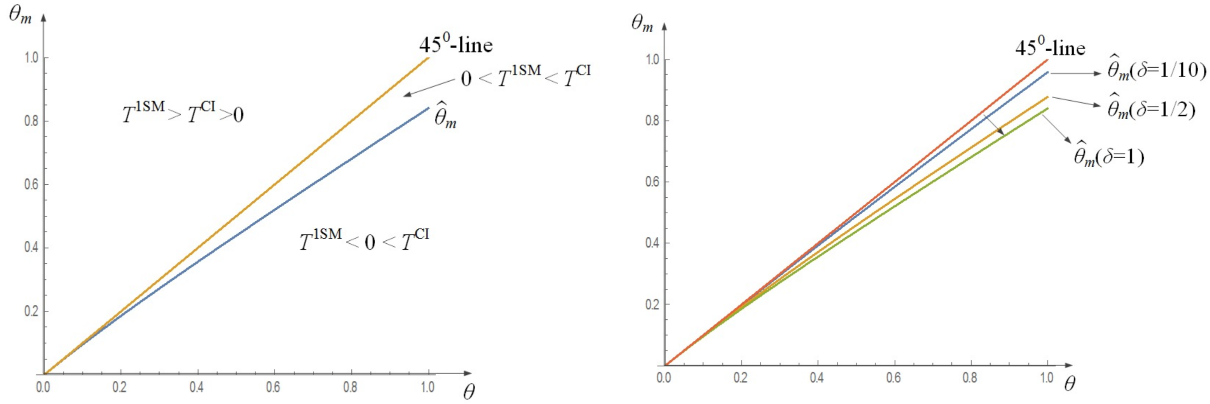
PROPOSITION 4. *The optimal transfer that induces the socially optimal levels of fungicide and all other inputs for growers $i$ and $j$, when grower $j$ is misinformed, is*

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

The optimal transfer when one grower is misinformed, $T^{1SM}$, decreases in the true fungicide resistance severity, $\theta$, and increases in the misinformed fungicide resistance severity, $\theta_m$. In addition, when $\theta_m = \theta$ transfers under complete information and one-side misinformation coincide, i.e., $T^{1SM} = T^{CI}$.

Figure 2a represents the cutoff $\widehat{\theta}_m$ that makes the optimal transfer under one-side misinformation, $T^{1SM}$, positive, where for illustration purposes we assume no discounting.[18] Therefore, for all the $(\theta, \theta_m)$-pairs above cutoff $\widehat{\theta}_m$ the transfer is positive. The figure also depicts the 45° line where $\theta_m = \theta$ and, thus, transfers satisfy $T^{CI} = T^{1SM}$. If the misinformed grower has very pessimistic beliefs about the severity of fungicide resistance ($\theta_m$ close to 1), the transfer is higher than that under complete information, $T^{CI}$, independent of the

[18] We obtain $\widehat{\theta}_m$ by making $T^{1SM} = 0$ and solving for $\theta_m$, obtaining $\widehat{\theta}_m = \frac{-2-\theta(4+\theta)+\sqrt{4(1+6\theta)+\theta^2(52+48\theta+17\theta^2)}}{2(1+2\theta)}$.




(a) $T^{2SM}$ and cutoff $\widehat{\theta}^{2SM}$.

(b) Cutoff $\widehat{\theta}^{2SM}$ at different values of $\theta_m^i$.

Figure 2

value of $\theta$. That is, grower $j$ is willing to pay an unnecessarily high transfer due to his wrong beliefs about $\theta$. However, if this grower holds very optimistic beliefs about the severity of fungicide resistance ($\theta_m$ close to 0), the transfer under misinformation is always lower than that under complete information, for all values of $\theta$. In fact, for all the ($\theta$, $\theta_m$)-pairs below cutoff $\widehat{\theta}_m$, the transfer becomes negative. Hence, an optimistic misinformed grower switches the roles in the compensation mechanism. That is, in order to achieve the socially optimal fungicide levels, grower $i$ (informed grower) pays a transfer to the misinformed grower. In this case, grower $j$ considers that fungicide resistance severity is insignificant, and he is only willing to participate in the compensation mechanism, choosing the socially optimal fungicides levels, if grower $i$ pays him a transfer. Figure 2b evaluates cutoff $\widehat{\theta}\theta_m$ on different values of $\delta$, showing that as future payoffs become less important ($\delta$ approaches zero), the negative intertemporal externality is less relevant and, hence, the area under which the transfer is positive shrinks. Next, we consider a setting in which both growers are misinformed.

## 3.2 Two-Sided Misinformation

In this subsection, we examine the consequences of growers $i$ and $j$ being simultaneously misinformed about fungicide resistance severity, for generality, where we allow for their misinformation to be symmetric and asymmetric. In particular, grower $i$ (grower $j$) wrongly believes that fungicide resistance severity is $\theta_m^i$ ($\theta_m^j$, respectively) where $\theta_m^i, \theta_m^j \neq \theta$; misinformation can be symmetric ($\theta_m^i = \theta_m^j$) or asymmetric ($\theta_m^i \neq \theta_m^j$). The following proposition presents their equilibrium input levels.

Proposition 5. *The equilibrium levels of fungicide when both growers are misinformed, $\widetilde{f}_{it}$, and all other inputs, $\widetilde{x}_{it}$, for every grower $i$, are*

*(i) in period 1:*

$$\widetilde{f}_{i1} = \frac{p^4 w^4}{64c^2 z^2 (1+\delta\theta_m^i)^2} \text{ and}$$

$$\widetilde{x}_{i1} = \frac{p^4 w^4}{32c^3 z (1+\delta\theta_m^i)};$$

*(ii) in period 2:*

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

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

*where input levels in both periods are strictly positive.*

Similar to the misinformed grower $j$'s fungicide levels in Proposition 3, grower $i$'s (grower $j$'s) fungicide levels are socially excessive if $\theta_m^i < 2\theta$ ($\theta_m^j < 2\theta$, respectively). That is, if misinformation leads growers to behave as if fungicide resistance is less than twice as severe as it actually is, then they will overuse fungicide. The distortionary consequences of misinformation are magnified in this scenario where neither grower has accurate information. We next evaluate the optimal transfer under two-sided misinformation.

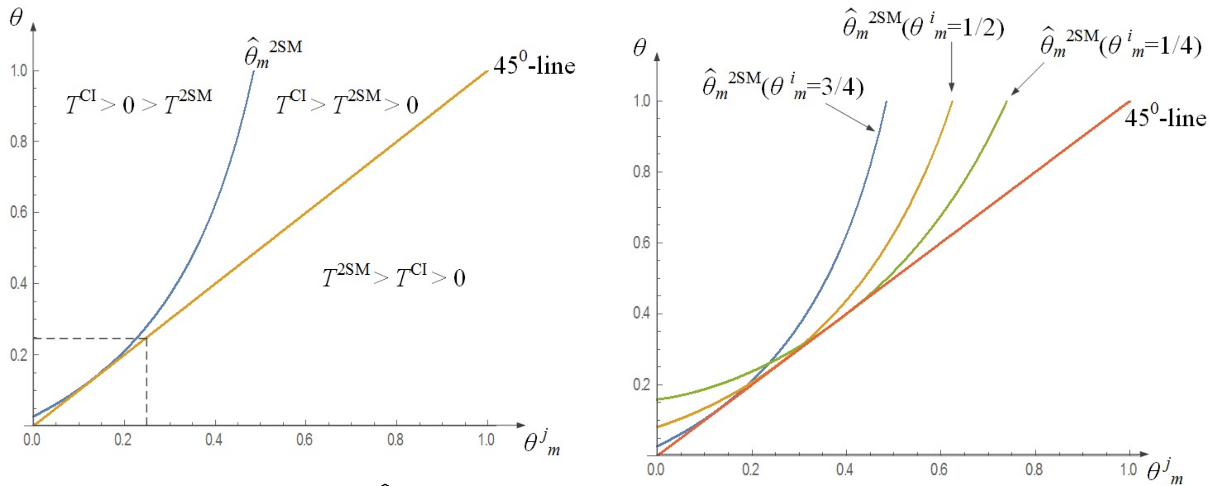
Proposition 6. *The optimal transfer that induces the socially optimal levels of fungicide* *and all other inputs for growers $i$ and $j$, when both growers are misinformed is*

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

Figure 3a depicts all pair $(\theta_m^j, \theta)$ combinations for which the transfer, $T^{2SM}$, is positive (below $\widehat{\theta}_m^{2SM}$). In order to graphically represent cutoff $\widehat{\theta}_m^{2SM}$ we fix $\theta_m^i = \frac{1}{4}$, in Figure 3a, but we consider different values of $\theta_m^i$ in Figure 3b.[19] As in Figure 2, the 45°-line represents all the points where $\theta_m^j = \theta$ and, hence, $T^{2SM} = T^{CI}$. For instance, if $\theta_m^j = \theta_m^j = \theta = \frac{1}{4}$ the transfer exactly coincides with that under complete information (see the dotted line in the figure). We also observe that when grower $j$ becomes very pessimistic about fungicide resistance severity, relative to grower $i$, ($\theta_m^j$ close to 1), the transfer is positive and above that under complete information, $T^{2SM} > T^{CI}$, for almost all values of $\theta$. However, if grower $j$ holds very optimistic beliefs about the severity of fungicide resistance ($\theta_m^j$ close to 0), $T^{2SM}$ becomes negative for almost all values of $\theta$. In this case, the compensation mechanism prescribes that the less optimistic grower $i$ ($\theta_m^i > \theta_m^j$) pays grower $j$ in order to achieve the socially optimal fungicide levels.

Figure 3b indicates that, as grower $i$ becomes more pessimistic about fungicide resistance severity, the area in which the optimal transfer is positive expands and $T^{2SM} > T^{CI}$ holds for more parameter values. For instance, if both growers hold pessimistic beliefs about fungicide resistance, i.e, $\theta_m^i = \theta_m^j = \frac{3}{4}$, but the true value of $\theta = \frac{1}{10}$, misinformation induces the compensation mechanism to select a transfer considerably above that under complete information. In this case, the difference between profits when misinformed growers do not internalize the intertemporal externality and those when they behave choosing the socially optimal level are sufficiently large, inducing an excessively high transfer.

[19] Figure 3a considers that $\theta_m^i = \frac{1}{4}$, $c = z = \frac{1}{2}$ and $p = w = \delta = 1$. Figure 3b assumes same parameter values, however, $\theta_m^i$ increases to $\frac{1}{2}$ and $\frac{3}{4}$.




(a) $T^{2SM}$ and cutoff $\widehat{\theta}^{2SM}$.

(b) Cutoff $\widehat{\theta}^{2SM}$ at different values of $\theta^i_m$.

Figure 3

## 3.3 Comparisons of Optimal Transfers

We next provide comparisons of transfers under different information settings. Note that social welfare comparisons do not provide further insights since the compensation mechanism induces the socially optimal input levels in equilibrium, independent of the information context. We provide a summary of the comparisons in the lemma below.

Lemma 2. *The optimal transfer under complete information, $T^{CI}$, is strictly lower than the transfer under*

1. *one-sided misinformation if $\theta_m > \theta$;*

2. *two-sided misinformation if:*

$$\theta^j_m < \widetilde{\gamma} \equiv \frac{\theta^i_m - 2\theta - \delta\theta^2 + (1+\delta\theta)\sqrt{\theta^i_m(1+\delta\theta^i_m)(\theta(2+\delta\theta) - \theta^i_m)}}{\delta(\theta(2+\theta) - \theta^I_m)}.$$

As indicated above, when only grower $j$ is misinformed the transfer is larger than that with complete information if he has pessimistic beliefs.

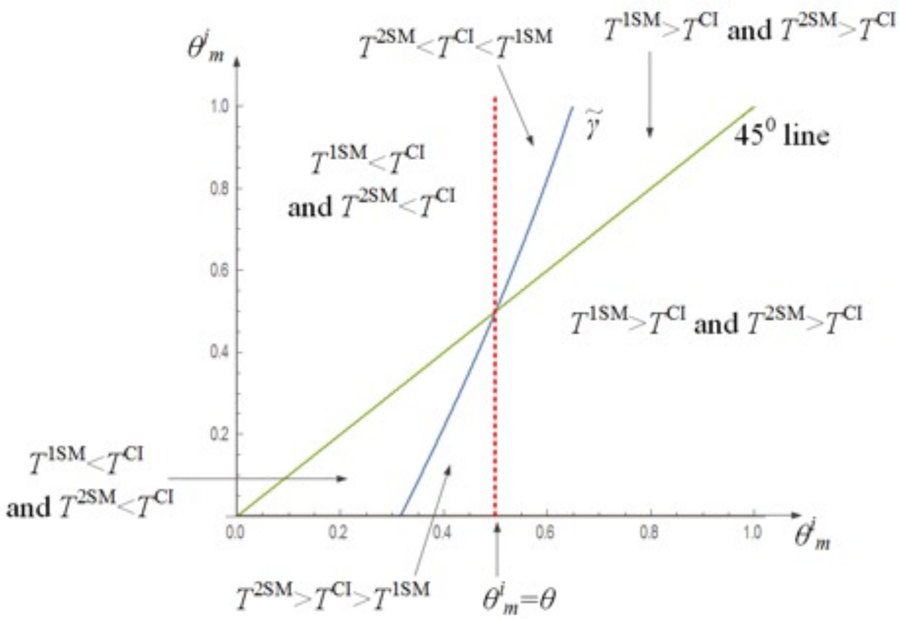



Figure 4

Figure 4 depicts the results in Lemma 2 considering, for presentation purposes, that $\theta = 1/2$ and $\delta = 1$. First, we show that the transfer under one-sided misinformation exceeds that under complete information if $\theta_m > \theta$. In a setting where grower $i$ is the only one misinformed, this condition is equivalent to $\theta^i_m > \theta$, as illustrated by the vertical line in the figure. Intuitively, if grower $i$ becomes more pessimistic (optimistic), transfers become higher (lower) than under complete information; as shown in the area to the right (left) of vertical line $\theta^i_m = \theta$ in the figure. Second, we demonstrate that the transfer under two-sided misinformation exceeds that under complete information if $\theta^j_m < \widetilde{\gamma}$, as represented by all $(\theta^i_m, \theta^j_m)$-pairs below cutoff $\widetilde{\gamma}$ in the figure. Intuitively, when growers sustain asymmetric beliefs, in the southwest of the figure, grower $i$ holds pessimistic beliefs while $j$ holds optimistic beliefs, leading to a higher transfer than under complete information. The opposite result holds in the northwest of the figure where, despite sustaining asymmetric beliefs, grower $i$ is now optimistic while $j$ is pessimistic, which generates a lower transfer than under complete information. In contrast, when growers are relatively symmetric in their (incorrect) beliefs, the transfer is higher (lower) under both one- and two-sided misinformation than under complete information if growers are pessimistic (optimistic), as depicted in the northeast (southwest) of the figure.

# 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 success of the compensation mechanism in reducing aggregate fungicide levels, and in turn fungicide resistance, critically depends 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 pessimistically misinformed about fungicide resistance severity, the compensation mechanism requires a greater transfer than in the complete information scenario, potentially affecting grower participation. This relationship is maintained when both growers are misinformed and they hold very asymmetric beliefs about the severity of fungicide resistance (i.e., grower $i$ ($j$) is very optimistic (pessimistic, respectively)). These findings similarly signal the importance of improving the access to accurate information about fungicide resistance for growers who participate in this compensation mechanism.

Our setting considers that growers already accept the terms of the compensation mechanism, which requires that one grower takes 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 in their profits. An additional avenue for future work is the development of a field experiment to test our theoretical results. This could shed some light on how transfers induce farmers to reduce their fungicide usage. Finally, it would be interesting to examine an intratemporal externality, in which fungicide levels in period 1 also affect pest occurrence in the current period. In this setting, growers face an additional cost from pest damage that enters in their profits.

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# A Appendix

## A.1 Proof of Proposition 1

In period 2, grower $i$ solves

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

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

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

Substituting $f_{i2}(\cdot)$ $x_{i2}$ provides us with the optimal value for other inputs in stage 2.

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

In period 1, grower $i$ solves

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

Substituting in the expressions from Period 2 and simplifying, we obtain

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

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.2 Proof of Lemma 1

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

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

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

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

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

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

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

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

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

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

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:

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

(ii) in period 2:

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

Next, we compare the fungicide levels from Proposition 1 with the socially optimal levels. Let us first compare fungicide levels in period 1.

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

implies

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

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

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

implies

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

This similarly holds given $\theta \in (0,1)$. Therefore, fungicide levels without compensation are socially excessive in both periods.

## A.3 Proof of Proposition 2

In period 2, grower $i$ solves

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

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

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

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

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

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

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

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

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

In period 1, grower $j$ chooses $x_{j1}$, $f_{j1}$ and $f_{i1}^R$ to maximize discounted aggregate profits. That is, they solve

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

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

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

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:

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

These input levels coincide with the socially optimal levels in Lemma 1. Let us consider grower $j$'s acceptable transfer (equation 7), that is,

$$\pi_{j1}(x_{j1}, f_{j1}) + \delta\pi_{j2}(x_{j2}, f_{j2}, f_{i1}^{SO}, f_{j1}^{SO}; T) \geq \pi_{j1}^*(x_{j1}, f_{j1}) + \delta\pi_{j2}^*(x_{j2}, f_{j2}, f_{i1}, f_{j1}).$$

To obtain the transfer that induces the socially optimal input levels we first identify the aggregate profits under no restrictions (right-hand side). Substituting fungicide and all other input levels from Proposition 1 we obtain

$$\pi_{j1}^*(x_{j1}, f_{j1}) + \delta\pi_{j2}^*(x_{j2}, f_{j2}, f_{i1}, f_{j1}) = \frac{p^4w^4\left(1+\delta[1+\delta\theta]^2\right)}{64c^2z(1+\delta\theta)^2}$$

Substituting socially optimal inputs levels from Lemma 1 into the aggregate profits (left-hand side) we have

$$\pi_{j1}(x_{j1}^{SO}, f_{j1}^{SO}) + \delta\pi_{j2}(x_{j2}^{SO}, f_{j2}^{SO}, f_{i1}^{SO}, f_{j1}^{SO}; T) = \frac{p^4 w^4 \left(1+\delta+2\delta^2\theta\right)}{64c^2 z(1+2\delta\theta)} - \delta T.$$

Combining these, the following must be satisfied

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

which holds, restricting our results to the admissible parameter values ($p, w, c, z > 0$ and $\theta, \delta \in (0,1)$), if

$$T^{CI} \leq \frac{\delta\theta^2 p^4 w^4}{64c^2 z(1+\delta\theta)^2(1+2\delta\theta)}.$$

Taking into account that grower $j$ pays $T^{CI}$, we focus on the maximum acceptable transfer which is

$$T^{CI} = \frac{\delta\theta^2 p^4 w^4}{64c^2 z(1+\delta\theta)^2(1+2\delta\theta)}$$

and is positive for all admissible parameter values. Note that

$$\frac{\partial T^{CI}}{\partial z} = -\frac{\delta\theta^2 p^4 w^4}{64c^2 z^2(1+\delta\theta)^2(1+2\delta\theta)} < 0 \text{ and}$$

$$\frac{\partial T^{CI}}{\partial \theta} = \frac{\delta\theta p^4 w^4(\delta\theta(1-\delta\theta)+1)}{32c^2 z(1+\delta\theta)^3(1+2\delta\theta)^2} > 0$$

since $\theta, \delta \in (0,1)$.

## A.4 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, $\pi_{j2}$.

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

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

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

In period 1, grower $i$'s problem coincides with that in Proposition 1. Grower $j$, however, solves

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

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:

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

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

(ii) in period 2:

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

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

## A.5 Proof of Corollary 1

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.6 Proof of Proposition 4

Let us consider grower $j$'s acceptable transfer (equation 7), and that he is misinformed (one-sided misinformation). That is, we consider

$$\pi_{j1}(x_{j1}, f_{j1}^{SO}) + \delta\pi_{j2}(x_{j2}, f_{j2}, f_{i1}^{SO}, f_{j1}^{SO}; T) \geq \pi_{j1}(\bar{x}_{j1}, \bar{f}_{j1}) + \delta\pi_{j2}(\bar{x}_{j2}, \bar{f}_{j2}, \bar{f}_{i1}, \bar{f}_{j1}).$$

We begin by identifying the aggregate profits with no restrictions (right-hand side). Substituting fungicide and all other input levels from Proposition 3 we obtain

$$\pi_{j1}(\bar{x}_{j1}, \bar{f}_{j1}) + \delta\pi_{j2}(\bar{x}_{j2}, \bar{f}_{j2}, \bar{f}_{i1}, \bar{f}_{j1}) = \frac{p^4 w^4 \left([1+\delta][1+\delta\theta]^2 + \delta\theta_m \left[\delta(1+\delta\theta)^2 - \delta\theta_m - 1\right]\right)}{64c^2 z(1+\delta\theta)^2 \left(1+\delta\theta_m\right)}$$

Substituting socially optimal inputs levels from Lemma 1 into the aggregate profits (left-hand side) we have

$$\pi_{j1}(x_{j1}^{SO}, f_{j1}^{SO}) + \delta\pi_{j2}(x_{j2}^{SO}, f_{j2}^{SO}, f_{i1}^{SO}, f_{j1}^{SO}; T) = \frac{p^4 w^4 \left(1+\delta+2\delta^2\theta\right)}{64c^2 z(1+2\delta\theta)} - \delta T.$$

Therefore, the optimal transfer under one-sided misinformation must satisfy

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

which holds, restricting our results to the admissible parameter values ($p, w, c, z > 0$ and $\theta, \delta \in (0,1)$), if

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

Considering that grower $j$ pays $T^{1SM}$, we focus on the maximum acceptable transfer which is

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

Note that when $\theta = \theta_m$

$$T^{1SM} = T^{CI} = \frac{\delta\theta^2 p^4 w^4}{64c^2 z(1 + \delta\theta)^2(1 + 2\delta\theta)}.$$

In order to obtain cutoff $\widehat{\theta}_m$, we make $T^{1SM} = 0$ and solve for $\theta_m$, which yields

$$\widehat{\theta}_m = \frac{-2 - \delta\theta(4 + \delta\theta) \pm \sqrt{4(1 + 6\delta\theta) + \delta^2\theta^2(52 + 48\delta\theta + 17\delta^2\theta^2)}}{2\delta(1 + 2\delta\theta)},$$

and considering that $\theta \in (0, 1)$ and assuming $\delta = 1$ we obtain

$$\widehat{\theta}_m = \frac{-2 - \theta(4 + \theta) + \sqrt{4(1 + 6\theta) + \theta^2(52 + 48\theta + 17\theta^2)}}{2(1 + 2\theta)}.$$

We next consider the case in which grower $i$ is misinformed and grower $j$ is informed. We first identify the aggregate profits under no restrictions (right-hand side). Substituting fungicide and all other input levels from Proposition 3 we obtain,

$$\pi_{i1}(\bar{x}_{i1}, \bar{f}_{i1}) + \delta\pi_{i2}(\bar{x}_{i2}, \bar{f}_{i2}, \bar{f}_{i1}, \bar{f}_{j1}) = \frac{p^4 w^4 \left([1 + \delta][1 + \delta\theta]^2 + \delta\theta_m \left[\delta(1 + \delta\theta)^2 - \delta\theta_m - 1\right]\right)}{64c^2 z(1 + \delta\theta)^2 \left(1 + \delta\theta_m\right)}$$

Substituting socially optimal inputs levels from Lemma 1 into the aggregate profits (left-hand side) we have

$$\pi_{i1}(x_{i1}^{SO}, f_{i1}^{SO}) + \delta\pi_{i2}(x_{i2}^{SO}, f_{i2}^{SO}, f_{i1}^{SO}, f_{j1}^{SO}; T) = \frac{p^4 w^4 \left(1 + \delta + 2\delta^2\theta\right)}{64c^2 z(1 + 2\delta\theta)} + \delta T.$$

Therefore, the optimal transfer when grower $i$ is misinformed must satisfy

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

which holds, at equality and restricting our results to the admissible parameter values ($p, w, c, z > 0$ and $\theta, \delta \in (0, 1)$), if

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

Notice that similar to before, also considering grower $i$'s perspective, if $\theta = \theta_m$ then

$$T^{1SM}=T^{CI}=-\frac{\delta\theta^2p^4w^4}{64c^2z(1+\delta\theta)^2(1+2\delta\theta)}.$$

## A.7 Proof of Proposition 5

We consider that grower $i$ and grower $j$ are asymmetrically misinformed; that is, $\theta_m^i \neq \theta$ and $\theta_m^j \neq \theta$, where $\theta_m^i \neq \theta_m^j$. We first need to calculate the input levels in this context. Operating by backward induction, we focus on the second stage where grower $i$ solves

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

Solving the first-order conditions yields

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

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

Simultaneously solving the above equations, we obtain

$$f_{\mathrm{i}2} = \frac{p^4 w^4}{64c^2 z^2} + \theta_m^i \left(f_{\mathrm{i}1} + f_{\mathrm{j}1}\right) \text{ and}$$

$$x_{\mathrm{i}2} = \frac{p^4 w^4}{32c^3 z}.$$

By symmetry, grower $j$'s input levels in the second stage are

$$f_{\mathrm{j}2} = \frac{p^4 w^4}{64c^2 z^2} + \theta_m^j \left(f_{\mathrm{i}1} + f_{\mathrm{j}1}\right) \text{ and}$$

$$x_{\mathrm{j}2} = \frac{p^4 w^4}{32c^3 z}.$$

In the first stage, grower $i$ solves

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

Substituting in $x_{i2}$ and $f_{i2}$, taking first order conditions, and solving the system yields the equilibrium results for the case where both growers are misinformed are

(i) in period 1:

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

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

(ii) in period 2:

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

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

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

## A.8 Proof of Proposition 6

To determine the transfer that induces the socially optimal input levels under asymmetric two-sided misinformation, we consider grower $j$'s acceptable transfer (equation 7), but also consider that both growers are misinformed (two-sided misinformation). Specifically, grower $i$ ($j$) believes that fungicide resistance severity is $\theta_m^i$ ($\theta_m^j$, respectively) where $\theta_m^i, \theta_m^j \neq \theta$ and $\theta_m^i \neq \theta_m^j$.

$$\pi_{j1}(x_{j1}, f_{j1}) + \delta\pi_{j2}(x_{j2}, f_{j2}, f_{i1}^{SO}, f_{j1}^{SO}; T) \geq \pi_{j1}(\widetilde{x}_{j1}, \widetilde{f}_{j1}) + \delta\pi_{j2}(\widetilde{x}_{j2}, \widetilde{f}_{j2}, \widetilde{f}_{i1}, \widetilde{f}_{j1}).$$

We first identify the aggregate profits with no restrictions (right-hand side). Substituting fungicide and all other input levels from Proposition 5 we obtain

$$\pi_{j1}(\widetilde{x}_{j1}, \widetilde{f}_{j1}) + \delta\pi_{j2}(\widetilde{x}_{j2}, \widetilde{f}_{j2}, \widetilde{f}_{i1}, \widetilde{f}_{j1})$$

$$= \frac{p^4 w^4 \left(1 + \delta\left[1 - \delta(\theta_m^i)^2 + \theta_m^i \left(\delta\left(1 + \delta\theta_m^j\right)^2 - 1\right) + (\delta+1)\theta_m^j\left(2 + \delta\theta_m^j\right)\right]\right)}{64c^2 z \left(1 + \delta\theta_m^j\right)^2 \left(1 + \delta\theta_m^i\right)}$$

Substituting socially optimal inputs levels from Lemma 1 into the aggregate profits (left-hand side) we have

$$\pi_{j1}(x_{j1}^{SO}, f_{j1}^{SO}) + \delta\pi_{j2}(x_{j2}^{SO}, f_{j2}^{SO}, f_{i1}^{SO}, f_{j1}^{SO}; T) = \frac{p^4 w^4 \left(1 + \delta + 2\delta^2\theta\right)}{64c^2 z(1 + 2\delta\theta)} - \delta T.$$

Therefore, the optimal transfer under two-sided asymmetric misinformation must satisfy

$$\frac{p^4 w^4 \left(1 + \delta + 2\delta^2\theta\right)}{64c^2 z(1 + 2\delta\theta)} - \delta T^{2SM}$$

$$\geq \frac{p^4w^4\left(1+\delta\left[1-\delta(\theta_m^i)^2+\theta_m^i\left(\delta\left(1+\delta\theta_m^j\right)^2-1\right)+(\delta+1)\theta_m^j\left(2+\delta\theta_m^j\right)\right]\right)}{64c^2z\left(1+\delta\theta_m^j\right)^2\left(1+\delta\theta_m^i\right)}$$

which holds, limiting our results to the admissible parameter values ($p, w, c, z > 0$ and $\theta, \delta \in (0,1)$), if

$$T^{2SM} \leq \frac{p^4w^4\left(\delta[\theta_m^i]^2[1+2\delta\theta]+\theta_m^i\left[2\delta\theta+\delta\theta_m^j\left(2+\delta\theta_m^j\right)+2\right]-2\theta\left(1+\delta\theta_m^j\right)^2\right)}{64c^2z(1+2\delta\theta)\left(1+\delta\theta_m^i\right)\left(1+\delta\theta_m^j\right)^2}$$

Considering that grower $j$ pays $T^{2SM}$, we focus on the maximum acceptable transfer which is

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

Note that when $\theta = \theta_m^i = \theta_m^j$

$$T^{2SM} = T^{CI} = \frac{\delta\theta^2p^4w^4}{64c^2z(1+\delta\theta)^2(1+2\delta\theta)}.$$

## A.9 Proof of Lemma 2

Using the optimal transfers from propositions 2, 4, and 6, we can make the following comparisons:

- *One-sided misinformation.*

  The complete information transfer (from Proposition 2) is strictly lower than that in the one-sided misinformation case (from Proposition 4) if

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

  which can only be satisfied, for admissible parameter values, if $\theta_m > \theta$.

- *Two-sided misinformation.*

The complete information transfer (from Proposition 2) is strictly lower than that in the two-sided misinformation case (from Proposition 6) if

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

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

Solving for $\theta_m^j$ we obtain two roots

$$\theta_m^j < \widetilde{\gamma} \equiv \frac{\theta_m^i - 2\theta - \delta\theta^2 + (1+\delta\theta)\sqrt{\theta_m^i(1+\delta\theta_m^i)(\theta(2+\delta\theta)-\theta_m^i)}}{\delta(\theta(2+\theta)-\theta_m^i)} \text{ and}$$

$$\theta_m^j > \widetilde{\gamma}' \equiv \frac{\theta_m^i - 2\theta - \delta\theta^2 - (1+\delta\theta)\sqrt{\theta_m^i(1+\delta\theta_m^i)(\theta(2+\delta\theta)-\theta_m^i)}}{\delta(\theta(2+\theta)-\theta_m^i)}.$$

However, cutoff $\widetilde{\gamma}' < 0$ for all $(\theta_m^i, \theta_m^j)$-pairs, then condition $\theta_m^j > \widetilde{\gamma}'$ holds for all $(\theta_m^i, \theta_m^j)$-pairs, implying that $T^{2SM} > T^{CI}$ holds if and only if $\theta_m^j < \widetilde{\gamma}$.

## A.10 Sensitivity Analysis

We consider several combinations of $\alpha$ and $\beta$. Note that there are two conditions that need to be satisfied, $\alpha > \beta$ (relatively greater elasticity of output to all other inputs rather than to fungicide) and $\alpha + \beta < 1$. We also show that fungicide levels are greater than the socially optimal levels in each scenario we consider.

| $\alpha$ | $\beta$ | $f^*_{i1}$ | $f^*_{i2}$ | $f^{SO}_{i1}$ | $f^{SO}_{i2}$ |
|---|---|---|---|---|---|
| $\frac{1}{2}$ | $\frac{1}{4}$ | $\frac{p^4w^4}{64c^2z^2(1+\delta\theta)^2}$ | $\frac{p^4w^4(1+2\theta[1+\delta]+\delta^2\theta^2)}{64c^2z^2(1+\delta\theta)^2}$ | $\frac{p^4w^4}{64c^2z^2(1+2\delta\theta)^2}$ | $\frac{p^4w^4\left(1+2\theta[1+2\delta]+4\delta^2\theta^2\right)}{64c^2z^2(1+2\delta\theta)^2}$ |
| $\frac{1}{2}$ | $\frac{1}{5}$ | $\frac{(pw)^{\frac{10}{3}}}{(10cz[1+\delta\theta])^{\frac{5}{3}}}$ | $\frac{(pw)^{\frac{10}{3}}([1+\delta\theta]^{\frac{5}{3}}+2\theta)}{(10cz[1+\delta\theta])^{\frac{5}{3}}}$ | $\frac{(pw)^{\frac{10}{3}}}{(10cz[1+2\delta\theta])^{\frac{5}{3}}}$ | $\frac{(pw)^{\frac{10}{3}}([1+2\delta\theta]^{\frac{5}{3}}+2\theta)}{(10cz[1+2\delta\theta])^{\frac{5}{3}}}$ |
| $\frac{2}{3}$ | $\frac{1}{5}$ | $\frac{32(pw)^{\frac{15}{2}}}{6075\sqrt{5}c^5z^{\frac{5}{2}}(1+\delta\theta)^{\frac{5}{2}}}$ | $\frac{32(pw)^{15/2}\left([1+\delta\theta]^{5/2}+2\theta\right)}{6075\sqrt{5}c^5\left(z^{5/2}[1+\delta\theta]^{5/2}\right)}$ | $\frac{32(pw)^{\frac{15}{2}}}{6075\sqrt{5}c^5z^{\frac{5}{2}}(1+2\delta\theta)^{\frac{5}{2}}}$ | $\frac{32(pw)^{15/2}\left([1+2\delta\theta]^{5/2}+2\theta\right)}{6075\sqrt{5}c^5\left(z^{5/2}[1+2\delta\theta]^{5/2}\right)}$ |
| $\frac{2}{3}$ | $\frac{1}{4}$ | $\frac{p^{12}w^{12}}{6561c^8z^4(1+\delta\theta)^4}$ | $\frac{p^{12}w^{12}([1+\delta\theta]^4+2\theta)}{6561c^8z^4(1+\delta\theta)^4}$ | $\frac{p^{12}w^{12}}{6561c^8z^4(1+2\delta\theta)^4}$ | $\frac{p^{12}w^{12}([1+2\delta\theta]^4+2\theta)}{6561c^8z^4(1+2\delta\theta)^4}$ |

We next compare the fungicide levels without compensation (except the comparisons of the main case in the paper shown in the proof of Proposition 1) to the socially optimal levels in each of the parameter cases listed above.

- **Case 1**: $\alpha = \frac{1}{2}$ $\beta = \frac{1}{5}$

  We begin first with fungicide levels in period 1.

$$f^*_{i1} \geq f^{SO}_{i1}$$

implies

$$\frac{(pw)^{\frac{10}{3}}}{(10cz[1+\delta\theta])^{\frac{5}{3}}} \geq \frac{(pw)^{\frac{10}{3}}}{(10cz[1+2\delta\theta])^{\frac{5}{3}}}.$$

This holds if $\theta \geq 0$, which is satisfied by the assumption we maintain that $\theta \in (0,1)$. In period 2,

$$f^*_{i2} \geq f^{SO}_{i2}$$

implies

$$\frac{(pw)^{\frac{10}{3}}\left([1+\delta\theta]^{\frac{5}{3}}+2\theta\right)}{(10cz[1+\delta\theta])^{\frac{5}{3}}} \geq \frac{(pw)^{\frac{10}{3}}\left([1+2\delta\theta]^{\frac{5}{3}}+2\theta\right)}{(10cz[1+2\delta\theta])^{\frac{5}{3}}}.$$

This similarly holds when $\theta \geq 0$ and so holds for all admissible parameter values.

- **Case 2:** $\alpha = \frac{2}{3}$ $\beta = \frac{1}{5}$

  In period 1,

$$f_{i1}^{*} \geq f_{i1}^{SO} \tag{12}$$

  requires

$$\frac{32\,(pw)^{\frac{15}{2}}}{6075\sqrt{5}c^5 z^{\frac{5}{2}}(1+\delta\theta)^{\frac{5}{2}}} \geq \frac{32\,(pw)^{\frac{15}{2}}}{6075\sqrt{5}c^5 z^{\frac{5}{2}}(1+2\delta\theta)^{\frac{5}{2}}}, \tag{13}$$

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

  In period 2,

$$f_{i2}^{*} \geq f_{i2}^{SO} \tag{14}$$

  implies

$$\frac{32(pw)^{15/2}\left([1+\delta\theta]^{5/2}+2\theta\right)}{6075\sqrt{5}c^5\left(z^{5/2}[1+\delta\theta]^{5/2}\right)} \geq \frac{32(pw)^{15/2}\left([1+2\delta\theta]^{5/2}+2\theta\right)}{6075\sqrt{5}c^5\left(z^{5/2}[1+2\delta\theta]^{5/2}\right)}. \tag{15}$$

  This similarly holds when $\theta \geq 0$ and so holds for all admissible parameter values.

- **Case 3:** $\alpha = \frac{2}{3}$ $\beta = \frac{1}{4}$

  In period 1,

$$f_{i1}^{*} \geq f_{i1}^{SO} \tag{16}$$

  requires

$$\frac{p^{12}w^{12}}{6561c^8z^4(1+\delta\theta)^4} \geq \frac{p^{12}w^{12}}{6561c^8z^4(1+2\delta\theta)^4}, \tag{17}$$

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

  In period 2,

$$f_{i2}^{*} \geq f_{i2}^{SO} \tag{18}$$

  implies

$$\frac{p^{12}w^{12}([1+\delta\theta]^4+2\theta)}{6561c^8z^4(1+\delta\theta)^4} \geq \frac{p^{12}w^{12}([1+2\delta\theta]^4+2\theta)}{6561c^8z^4(1+2\delta\theta)^4}. \tag{19}$$

  This similarly holds when $\theta \geq 0$ and so holds for all admissible parameter values.