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, the noncooperative fungicide level is higher than the socially optimal level. We examine a compensation mechanism designed to ameliorate fungicide resistance and find that it induces the socially optimal level; however, misinformation about the severity of the fungicide resistance generates distortions. The results suggest that the information available to growers about fungicide resistance is essential for its mitigation with the proposed compensation mechanism. In particular, we find that if the misinformed grower considers fungicide resistance to be relatively mild, then it is preferable that the misinformed grower has the compensating role.

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 are economically dependent upon fungicides as fungicide-based management has been deemed responsible 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, which not only has cost implications for grape growers, but also negative environmental and health consequences.[2] The challenge of addressing fungicide resistance is in part a collective action problem and, therefore, efforts to mitigate it can benefit from increased understandings of the strategic choices of grape growers in their selection of fungicide levels.

Our paper answers 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), and Martin (2015),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 unique policy that can facilitate the internalization of fungicide resistance, and negative intertemporal production externalities more generally.

A central contribution of our analysis is the examination of a compensation mechanism to address this problem. It belongs to the second of the two policy approaches discussed by Regev et al. (1983); namely, rather than examining a subsidy as in Martin (2015), we study

[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]For more details see Christ and Burritt (2013).

a compensation mechanism that depends upon both the restriction of fungicide levels for certain growers[3],[4] and any corresponding loss in their profits.[5] One of its main advantages is that it does not require mandating fungicide levels unilaterally for all growers in all periods. Another advantage of our mechanism is its cooperative nature. Lemarié and Marcoul (2018), using a distinct modeling framework, show that growers benefit from coordination in the context of managing fungicide resistance. By implementing our compensation mechanism, and allowing for growers to freely choose the majority of their input levels, our policy is less restrictive than a subsidy or quota.

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.[6] 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

[3]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.

[4]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.

[5]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.

[6]Pimentel (2005) discusses the compounding problem of fungicide resistance as a subcategory of pesticide resistance in pests, which is a serious global environmental problem, and estimates that the costs of pesticide resistance are more than $1.5 billion a year in the United States alone.

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, 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 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 policymakers even if the growers must use the 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."[7] 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

[7] For more details see: https://framenetworks.wsu.edu/

about the fungicide resistance severity, and iv) an extension of the game where we apply our compensation mechanism in the context where misinformation exists. By considering a setting in which a grower is misinformed about the severity of fungicide resistance, we are able to evaluate the distortions generated by misinformation with our compensation mechanism. In addition, we provide comparisons between the fungicide levels of these models and the socially optimal level.

Similar to Sims et al. (2018), Liu and Sims (2016) and Bhat and Huffaker (2007), but in a different modeling setting, we find that our proposed compensation mechanism successfully reduces aggregate fungicide usage to the socially optimal level in the case of complete information. However, the success of this mechanism becomes less certain when we allow for misinformation. 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. Therefore, a compensation mechanism designed to mitigate fungicide resistance by restricting fungicide use and compensating growers for their lost profits is more effective if all growers are well informed about the severity of the externality.

Given the role of each player in the compensation mechanism, 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 they think that fungicide resistance will be more severe than it is in reality. If policymakers 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.

When a policymaker seeks to mitigate the losses to growers' aggregate profits under misinformation, then it is best if the level of misinformation is low or nonexistent. This underscores the importance of educational efforts about fungicide resistance severity.[8] 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 compensation mechanism to be implemented in a setting where growers have precise information about the 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 results in fungicide resistance that reduces its effectiveness in production in the next 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

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

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

[8] 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.[9] 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. 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 is determined by a fungicide-resistance parameter. We consider this sensitivity parameter to be $\theta \in (0, 1)$. If θ is close to zero, then the fungicide-resistance externality has a negligible impact on production. Conversely, if θ approaches one then the externality is very severe and its impact on production is high. Finally, α and β are parameters where $\{\alpha, \beta\} \in (0, 1)$. 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 represents the cost of applying fungicide (with marginal cost 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.[10] Note that in the first period growers do not face the future consequences of their fungicide use. In the second period, the profit function for grower i is

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

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

[10] 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 introduce a compensation mechanism of the following form: grower i voluntarily restricts fungicide use provided that grower j compensates them for their 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 where the production externality resulting from the aggregate fungicide level from the first period enters in the second period. Therefore, 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 $\alpha = \frac{1}{2}$ and $\beta = \frac{1}{4}$, which facilitates the provision of meaningful results. Note that the model becomes intractable if we allow for general values of these parameters.[11] We next solve the game using backward induction.

Stage 2

In this context, 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

[11] With the Cobb-Douglas production technology, α and β 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. Our results are not qualitatively affected if we consider different parameter values as long as $\alpha > \beta$ and $\alpha + \beta < 1$.

period, which we present in the following lemma.

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 optimal levels of fungicide in the second period are increasing in the aggregate fungicide levels in the first period. This relationship indicates that the growers adjust their second-period levels of fungicide use given the fungicide resistance stemming from period 1.

Stage 1

In the first stage, growers choose their input levels to maximize the present value of their profits in the game. 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 θ for every period t.

Note that 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 far these 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 the social planner 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:

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

(ii) in period 2:

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

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 game without the compensation mechanism and the social planner's problem.

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 their 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 a regulator can use to induce 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 their fungicide level in the first period, which contributes to the effect of fungicide resistance 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.[12]

Similar to the game without compensation, we apply backward induction. To begin, we determine a compensation level that leads to both growers participating in the policy. 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 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

[12] We consider only that the transfer occurs in the second period given that in reality it is likely growers would only have enough resources to provide the transfer at the end of the coordination period. Moreover, we think it is unlikely that growers would be willing to compensate before they could be assured that fellow growers cooperated as planned.

period 1 fungicide, f_{i1}^R , and makes the transfer, T, to grower i is

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

Note that 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 grower i and j become

$$\pi_{i2}(x_{i2}, f_{i2}, f_{i1}^R, f_{j1}) = pw(x_{i2})^{\frac{1}{2}}(f_{i2} - \theta[f_{i1}^R + f_{j1}])^{\frac{1}{4}} - cx_{i2} - zf_{i2} + T \text{ and}$$

$$\pi_{j2}(x_{i2}, f_{i2}, f_{i1}^R, f_{j1}) = pw(x_{j2})^{\frac{1}{2}}(f_{j2} - \theta[f_{i1}^R + f_{j1}])^{\frac{1}{4}} - cx_{j2} - zf_{j2} - T.$$

Here, though grower i is being restricted in period 1 fungicide levels, they are compensated by grower j for any resulting loss of profits. 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:

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

(ii) in period 2:

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

As before, we are concerned with how close these levels are to socially optimal levels. 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.[13] This exact compensation renders grower i willing to limit inputs in period 1 to socially optimal levels. In the next section, we consider an extension of the model where 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 assumes a fungicide resistance severity. 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 still knows the true severity of fungicide resistance, but grower j is misinformed. That is, rather than knowing the true θ, grower j assumes a different fungicide resistance severity ($\theta_m \neq \theta$) when choosing inputs. 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 mechanism.

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:

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

[13] Note that 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.

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

(ii) in period 2:

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

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

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 they know the true value of θ (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 their period 1 choice of fungicide level. 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 the compensation mechanism. Their fungicide use coincides with the socially optimal level when $\theta_m = 2\theta$.*

Upon examination, we find that if grower j assumes that fungicide resistance is more than twice as severe as it is in reality ($\theta_m > 2\theta$), then they choose a fungicide level that is strictly lower than socially optimal (see Figure 1, Region A). Conversely, grower j chooses a socially excessive amount if they consider 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 they consider that fungicide resistance is twice as severe as it actually is ($\theta_m = 2\theta$, see Figure 1).[14] In that case, the misinformation would inadvertently lead the misinformed grower to select the socially optimal choice.

[14]We also examined the case where the growers collaborate 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 in the second-best case.

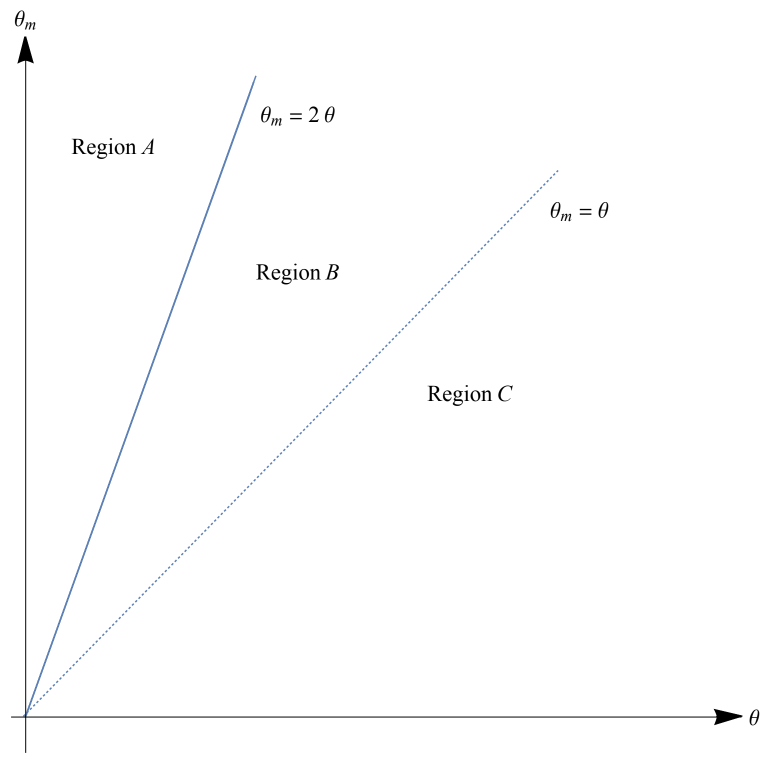

Figure 1: Grower j is misinformed.

In the following proposition, we present the results incorporating 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*

(i) in period 1:

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

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

(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.

To again provide actionable discussion for policymakers, 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) with the compensation mechanism.*

If grower j thinks that fungicide resistance is more severe than it is in reality ($\theta_m > \theta$), then their period 1 fungicide level choice is always lower than socially optimal (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.[15]

Therefore, the success of the compensation mechanism 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 they think that fungicide resistance will be 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 examine the case wherein the grower who receives the compensation, grower i, is misinformed about the severity of fungicide resistance.[16] Next,

[15] 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).

[16] 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

we share the equilibrium results associated with this scenario and focus on the case with compensation.[17]

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:

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

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

(ii) in period 2:

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

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

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

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

Grower i's first-period fungicide level in this scenario is always higher than socially optimal when fungicide resistance is not so severe 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.

mechanism).

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

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 thinks that fungicide resistance will 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. 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), is strictly increasing in the misinformed fungicide resistance severity (i.e., θ_m). This response is the driver of the positive relationship between aggregate fungicide use and the misinformed fungicide resistance severity. Though under certain conditions the misinformed grower who receives compensation (i.e., grower i) decreases fungicide usage in period 1 when θ_m increases, the effect of the informed grower's response dominates.

For policymakers who seek to apply the compensation mechanism to achieve the socially optimal input levels in each period, the first-best scenario would be that all growers are perfectly informed about fungicide resistance severity (e.g., via effective and widespread education). In the context of misinformation, the success 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 policymakers seeking to reduce future fungicide resistance before 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. To facilitate comparisons that provide guidance for policymakers 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.[18]

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 2 and Figure 3 showing the differences in social welfare (SW) for relatively mild fungicide resistance between the social planner's problem and the corresponding misinformation scenarios with compensation (i.e., Figure 2 compares the social welfare of the social planner's problem with subsection 3.1 and Figure 3 compares it with subsection 3.2). They show 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

[18]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. Different parameter values do not change the qualitative results and can be provided upon request by the authors.

social planner's problem is strictly greater except where both growers are well informed (i.e., $\theta_m = \theta$). This is mirrored in the case of severe fungicide resistance.

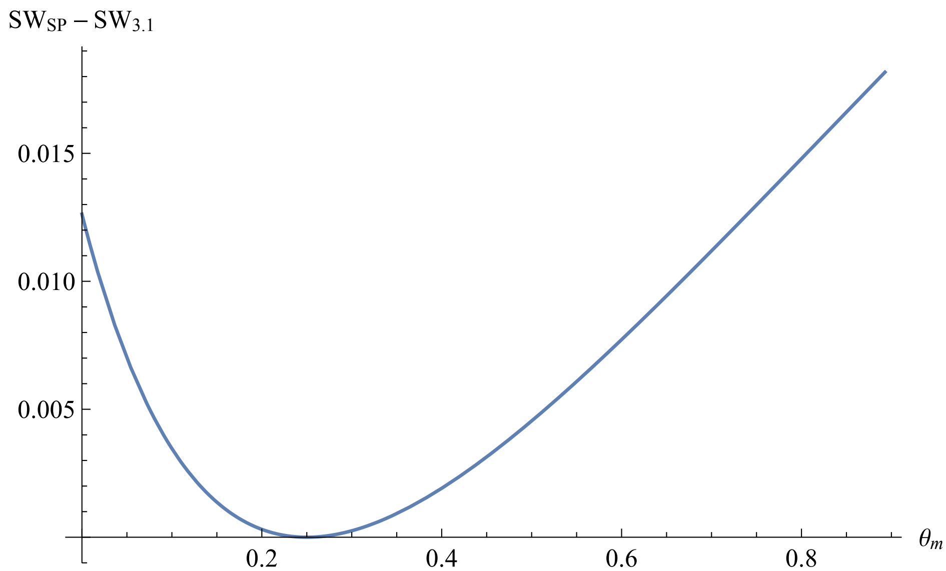

Figure 2: Mild fungicide resistance with misinformed grower j.

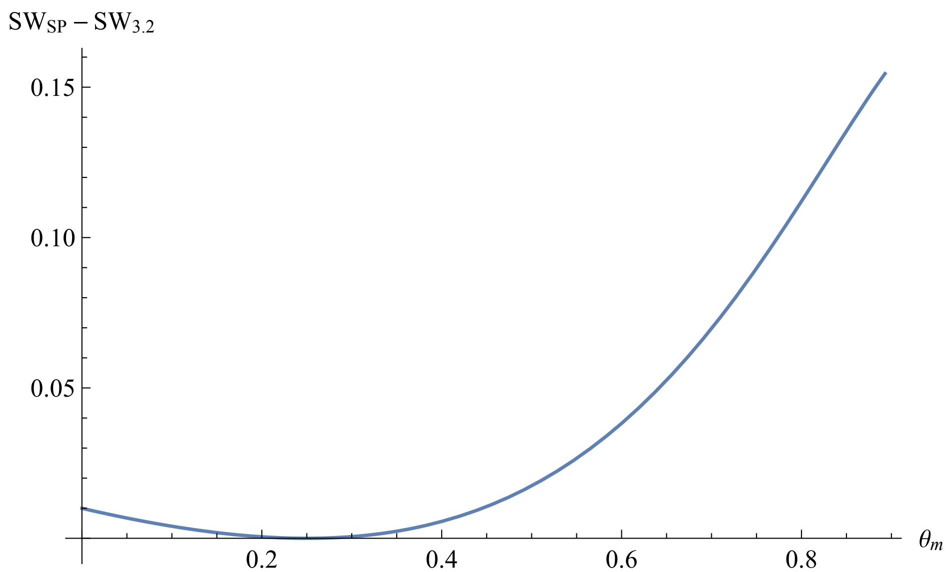

Figure 3: Mild fungicide resistance with misinformed grower i.

Therefore, as noted in Corollary 6, the compensation mechanism cannot bring aggregate profits to the socially optimal level when there is misinformation. In light of this, we provide guidance that will allow for policymakers who apply this compensation mechanism to be aware of what can reduce this difference. We include figures 4 and 5 to illustrate the difference between social welfare of the scenarios illustrated in subsections 3.1 and 3.2, respectively,[19] as a grower's misinformed assumption about fungicide resistance severity changes.

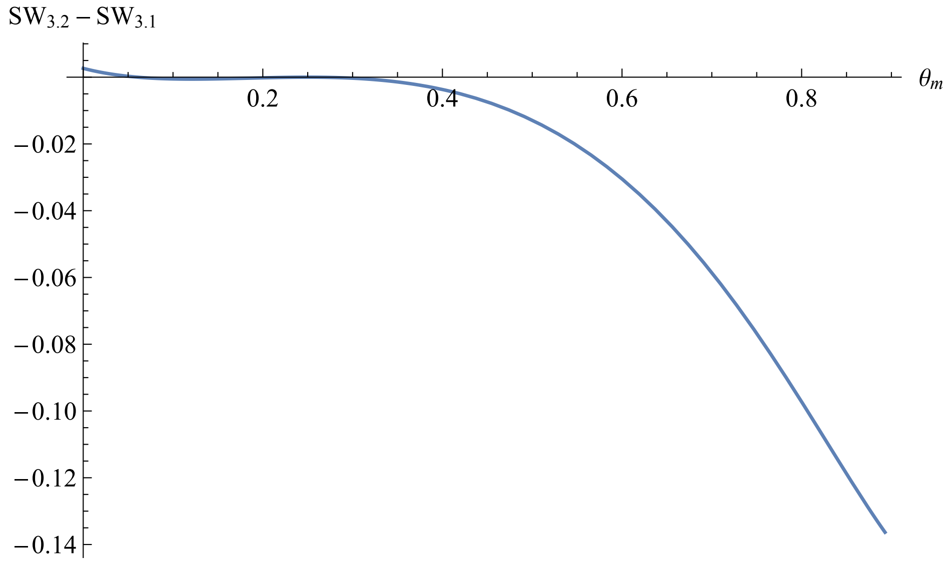

Figure 4: Mild fungicide resistance.

[19]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.

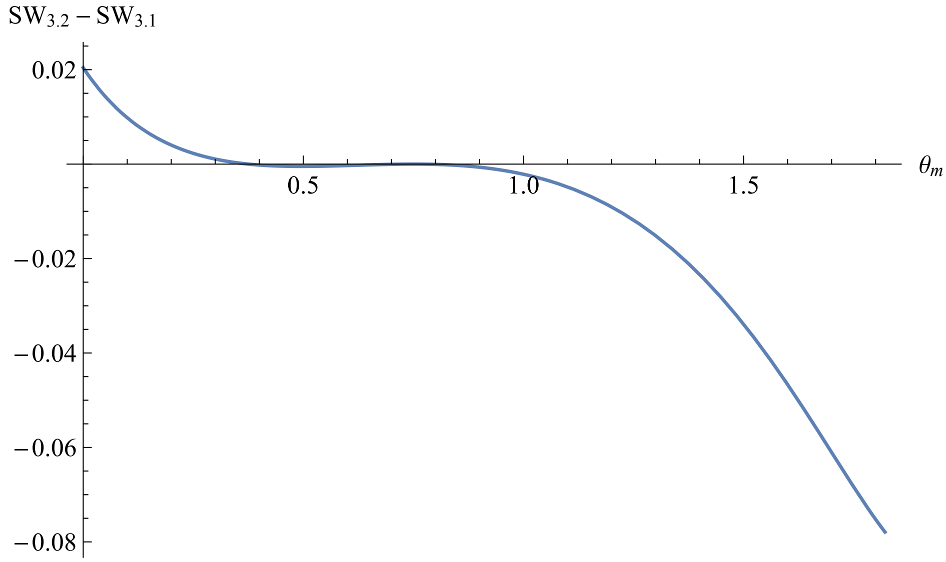

Figure 5: Severe fungicide resistance.

We observe that if the misinformed grower considers fungicide resistance to be more severe than it actually is, 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, 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 success of the compensation mechanism 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). Therefore, education about fungicide resistance severity is not only helpful in terms of the overall success of the compensation mechanism (as illustrated by figures 3 and 4), but for its relative success under different scenarios of misinformation.

4 Conclusion

We examine the consequences of the intertemporal production externality of fungicide resistance for grape growers. We propose a unique compensation mechanism to correct for the externality in contexts of both perfect information and of misinformation.

We find that, without the compensation mechanism, growers fail to internalize the intertemporal production externality of fungicide resistance and choose fungicide levels that are higher than socially optimal. Under complete information, the compensation mechanism we propose successfully induces socially optimal fungicide levels.

Our results indicate that the success of the compensation mechanism in reducing aggregate fungicide levels, and in turn quantitative 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 success of a social welfare improving compensation mechanism. Our findings suggest that if misinformation persists among some growers, it is most 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.

A natural extension of our model is a context in which the regulator can decide the role of each grower in the contract. An additional avenue for future work that arises from our paper is the context where a well-informed grower can signal the true state of fungicide resistance severity to a neighboring grower.

References

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, 2

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. 4

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. 2

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, 2

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

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, 4

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

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. 2

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, 3

Richards, T. J. and P. M. Patterson (2003). Competition in Fresh Produce Markets: An Empirical Analysis of Marketing Channel Performance. Technical Report September, United States Department of Agriculture. 6

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. 6

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, 4

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

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

A Appendix

A.1 Proof of Lemma 1

Period 2

In period 2, grower i chooses x_{i2} and f_{i2} to maximize their profits, π_{i2}. That is, they solve

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

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

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

We select the strictly positive values for our analysis. Next, utilizing the best-response function from Lemma 1, in conjunction with the first-order condition for x_{i2}, provides us with the optimal value for other inputs in stage 2.

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

A.2 Proof of Proposition 1

Period 1

In period 1, grower i chooses x_{i1} and f_{i1} to maximize discounted aggregate profits. That is, they solve

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

Substituting in the expressions from Period 2 (see 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 solve for optimal levels of fungicide in both periods and for optimal level of other inputs in period 1 for grower i. Therefore, the equilibrium results 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:

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

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 over the course of the game.

Period 2

In period 2, the social planner chooses input levels for both growers to maximize the sum of their profits. That is, they solve

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

For which the corresponding first-order conditions are

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

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

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

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

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:

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

The first-order conditions also allow for us to find $f_{i2}(f_{i1},f_{i1})$ and $f_{j2}(f_{i1},f_{i1})$.

Period 1

In period 1, the social planner chooses x_{i1} and f_{i1} to maximize the sum for the whole game the of discounted aggregate profits. That is, they solve

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

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

Note that in period 1 the social planner substitutes in the equations found in period 2. After doing this, the associated first-order conditions are

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

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

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

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

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 Proposition 2

Period 2

Grower i

In period 2, grower i chooses x_{i2} to maximize their profits, π_{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

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

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

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

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

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

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.

Grower j

In period 2, they choose x_{j2} and f_{j2} to maximize their profits, π_{j2}. That is, they solve

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

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

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

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.

We next substitute the selected expressions for $f_{i2}(f_{i1}^R, f_{j1})$, $f_{j2}(f_{i1}^R, f_{j1})$, $\hat{x}_{i2}$, and $\hat{x}_{j2}$ into the compensation T, and the maximizations for Period 1.

Period 1

Grower j

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

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

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

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

Grower i

In period 1, grower i chooses x_{i1} to maximize discounted aggregate profits. That is, they solve

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

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 solve for optimal levels of fungicide in both periods and for optimal level of other inputs in period 1. Therefore, the results of this game are

(i) in period 1:

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

(ii) in period 2:

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

A.5 Proof of Proposition 3

Period 2

In period 2, because grower i is perfectly informed, their choices coincide with those from Proposition 1.

In period 2, grower j chooses x_{j2} and f_{j2} to maximize their profits, π_{j2}. Because they are misinformed about fungicide resistance severity, they solve

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

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

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

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

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

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

As before, we select the strictly positive values for our analysis.

We next substitute the selected expressions for $f_{i2}(f_{i1}, f_{j1})$ and $f_{j2}(f_{i1}, f_{j1})$, along with the expressions for x^*_{i2} and x^*_{j2} into the growers' maximizations for Period 1.

Period 1

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

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

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

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

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

We solve for the optimal levels of fungicide in both periods and for optimal level of other inputs in period 1 for both growers. The equilibrium results are

(i) in period 1:

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

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

(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.6 Proof of Proposition 4

Period 2

Grower i

In period 2, grower i chooses x_{i2} to maximize their profits, π_{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

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

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

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

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

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

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.

Grower j

In period 2, they choose x_{j2} and f_{j2} to maximize their profits, π_{j2}. That is, they solve

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

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

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

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

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

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

As before, we select the strictly positive values for our analysis. We next substitute the selected expressions for $f_{i2}(f_{i1}^{R}, f_{j1})$, $f_{j2}(f_{i1}^{R}, f_{j1})$, $\hat{x}_{i2}$, and $\hat{x}_{j2}$ into the compensation T, and the maximizations for Period 1.

Period 1

Grower j

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

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

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

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

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

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

Grower i

In period 1, grower i chooses x_{i1} to maximize discounted aggregate profits. That is, they solve

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

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

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

Using the first-order conditions and the previously obtained expressions, we solve for optimal levels of fungicide in both periods and for optimal level of other inputs in period 1. Therefore, the results of this game are

(i) in period 1:

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

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

(ii) in period 2:

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

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

A.7 Proof of Proposition 5

Period 2

Grower i

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

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

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

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

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

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

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.

Grower j

In period 2, they choose x_{j2} and f_{j2} to maximize their profits, π_{j2}. That is, they solve

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

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

$$-pw\sqrt[4]{f_{i1}^R}\sqrt{x_{i1}} + zf_{i1} + \delta zf_{i2} + pw\sqrt[4]{f_{j1}}\sqrt{x_{j1}} - zf_{j1} - \delta zf_{j2}].$$

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. We next substitute the selected expressions for $f_{i2}(f_{i1}^R, f_{j1})$, $f_{j2}(f_{i1}^R, f_{j1})$, $\hat{x}_{i2}$, and $\hat{x}_{j2}$ into the compensation T, and the maximizations for Period 1.

Period 1

Grower j

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

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

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

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

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

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

From these first-order conditions we can obtain the equilibrium input levels for grower j and a condition that grower i must abide by. We will present all equilibrium levels together at the end of the proof.

Grower i

In period 1, grower i chooses x_{i1} to maximize discounted aggregate profits. That is, they solve

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

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:

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

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

(ii) in period 2:

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

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

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

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.

A.8 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

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

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 figures to illustrate the cases for when grower i, the compensated grower, is misinformed.

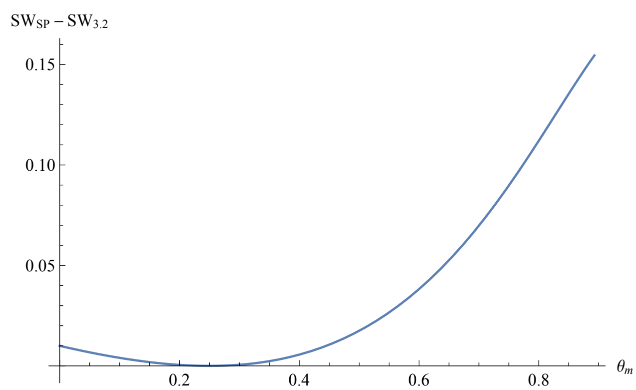

Figure 6: Mild fungicide resistance with misinformed grower i.

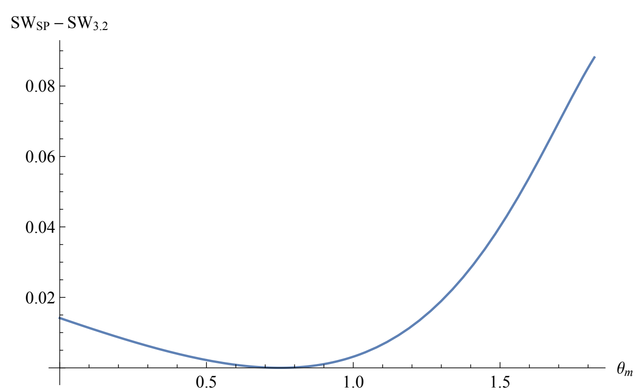

Figure 7: Severe fungicide resistance with misinformed grower i.

We find that, similar to when grower j is misinformed, social welfare in both cases only coincides when grower i is not misinformed.