Adverse Selection, Moral Hazard, and Grower Compliance with Bt Corn Refuge

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Abstract

This paper develops a principal-agent model of farmer compliance with Bt corn refuge requirements intended to manage the evolution of resistance to the Bt toxin by insect pests. The model endogenizes the price of the technology, the audit rate, and the fine imposed on non-complying farmers when farmer willingness to pay for Bt corn and compliance effort is private information.

Key words: asymmetric information, Compliance Assurance Program, European corn borer, insect resistance management, principal-agent model.

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Bt corn is a popular term used to describe corn engineered to contain genetic material from the bacterium *Bacillus thuringiensis* (Bt). Bt corn produces proteins toxic to insects such as the European corn borer *Ostrinia nubilalis* (ECB)—a pest estimated to cost farmers over $1 billion annually in yield loss and control costs (Mason et al.). Bt corn offers complete control of the targeted pest, which has resulted in its rapid adoption in the U.S. since commercial introduction in 1996. Over 25% of all corn acreage in the U.S. was planted to Bt corn in 2003, with higher adoption rates in areas with larger yield losses from ECB damage (USDA-NASS 2003a).

Accompanying the excitement over the benefits of Bt corn is worry that European corn borer will develop resistance to Bt corn. Current resistance management for Bt corn is based on a high dose-refuge strategy that requires growers to plant non-Bt corn as a refuge (Ostlie, Hutchison, and Hellmich). This refuge generates ECB not exposed to Bt corn that mate with resistant ECB emerging from nearby Bt corn. The goal is to produce an overwhelming number of susceptible ECB for every resistant ECB (at least 500:1) and thus slow the proliferation of resistance genes and prolong the efficacy of Bt. The refuge requirement has two primary components—a size requirement that varies depending on the region (20-50%) and a placement requirement (within one-half mile). If growers do not plant the required refuge, resistance will evolve more quickly (Hurley, Babcock, and Hellmich). At this time, no viable field population of an insect pest resistant to Bt has been detected, but at least seven laboratory colonies of three insect species have developed resistance to Bt proteins (Fox; Tabashnik et al.).

Surveys show that though most growers comply with refuge requirements, significant non-compliance exists. For example, an industry-sponsored survey of growers planting at least 200 acres of Bt corn in 2003 found that 92% of growers met the refuge size requirement and 93% met the refuge placement requirement, a substantial increase over previous years (National

Corn Growers Association). However, 2002 USDA-NASS data indicates that 19% of all farms planting Bt corn in Iowa, Minnesota, and Nebraska violated the refuge size requirement, with 13% not planting any refuge (Jaffe).

As a result of compliance concerns, the EPA required Bt corn registrants to develop a specific program to monitor and encourage refuge compliance among growers. Together these companies announced the Compliance Assurance Program on November 15, 2002 with EPA approval (Agricultural Biotechnology Stewardship Technical Committee). Among the programs many components, growers who do not comply with the refuge requirement for two consecutive years will be denied access to Bt corn in the third year from all companies. Company representatives visited some farms in 2003 to determine Bt corn refuge compliance and farms found not in compliance are guaranteed a visit during 2004. However, the effectiveness of the program at ensuring compliance remains to be established. The issue is whether the program’s punishment is enforceable, since the registrants have licensed many seed companies to sell Bt corn, and whether the ban is an effective deterrent.

This paper conceptually and empirically evaluates a fine program to ensure compliance. The program randomly selects Bt corn growers for compliance audits, just as the Compliance Assurance Program. But instead of a ban for repeated noncompliance, non-complying growers pay a fine. To derive the optimal audit rate and fine, we develop a principal-agent model with a Bt corn registrant (a seed company) as the principal and growers as the agents. We first develop a conceptual model, and then build an empirical model to evaluate the practical application of a fine based compliance program.

Conceptual Model

We develop a principal-agent model of the Bt corn refuge compliance problem with two types of asymmetric information that create adverse selection and moral hazard problems for a seed company. First, a grower's willingness to pay for Bt corn is private information, though the company knows the distribution of the willingness to pay among growers. Second, a grower's compliance effort is private information, but becomes known to the company if the grower is audited. The company chooses the price of Bt corn, the audit rate, and the fine to charge for non-complying growers, given both types of asymmetric information.

Currently, farmers who purchase Bt corn must sign or renew a grower agreement confirming their awareness of the refuge requirements. With a fine program, a portion of these growers is randomly selected for a compliance audit. Auditors visit the selected growers and determine whether the farm is in compliance. For the fine program, noncomplying growers pay a fine while complying growers do not pay a fine or receive a payment. The company chooses the audit rate, the grower fine, and the price to charge for Bt corn to maximize expected net returns from selling Bt corn and collecting fines, and paying costs for monitoring and the development of ECB resistance. The company must account for the effect the price has on the type of growers who buy Bt corn and their compliance, as well as ensure that the expected fine gives growers appropriate incentives to comply.

Grower Returns, Participation, and Incentive Compatibility

Yield for conventional corn is $y(1 - \lambda)$, where y is random potential (pest-free) yield and λ is the random proportion of yield lost due to ECB damage. Because Bt corn provides essentially complete ECB control, yield for Bt corn is simply potential yield y (Mitchell et al.). As a result, per acre returns for a grower planting conventional corn are $\pi_{cv} = py(1 - \lambda) - K$, where p is the random price of corn and K is the non-random production cost. Per acre returns for a non-complying grower who plants all Bt corn without paying extra for it are $\pi_{bt} = py - K$. We focus only on the size requirement for refuge, so that growers choose the proportion ϕ of their corn to plant as non-Bt corn refuge. The required proportion of refuge is $\phi = \phi_c$, so that returns for a complying grower are $\pi_{cp} = \phi_c\pi_{cv} + (1 - \phi_c)\pi_{bt}$. Per acre returns when the grower complies and pays an additional per acre cost for Bt corn are $\pi_{cp} - (1 - \phi_c)T$, where T is the non-random price of Bt corn usually identified with the technology fee. We assume y and λ are independent (Mitchell et al.; Hurley, Mitchell, and Rice).

Growers maximize expected utility of per acre profit, knowing the cost of production K, and the distribution of pest-free yield y, price p, and proportional yield loss λ. The company also knows K, these distributions, and the expected utility maximizing behavior of growers. However, a grower's maximum per acre willingness to pay W for Bt corn is private information known only to the grower, where W is implicitly defined by

$$\text{E}[U(\pi_{cp} - W)] = \text{E}[U(\pi_{cv})]. \tag{1}$$

W can also be considered a monetary measure of a grower's welfare benefits from planting Bt corn (Hurley, Mitchell, and Rice). From the company's perspective, W is a random variable with known distribution function $G(W)$ and density function $g(W)$ describing its distribution among growers. Using standard adverse selection terminology, W defines a grower's hidden type, but the distribution of W among growers is common knowledge (Laffont and Martimort).

A grower's compliance effort is ϕ, the proportion of corn acres the grower plants as non-Bt corn refuge. This effort ϕ is private information known only to the grower, so that this potential for hidden action creates a moral hazard problem (Laffont and Martimort). Though a grower's choice of compliance effort ϕ is continuous, we follow the applied moral hazard literature (Laffont and Martimort, p. 200) and focus on two cases. Grower effort is either high, that is the grower complies and plants the required refuge $\phi = \phi_c$, or grower effort is low, that is the grower plants no refuge ($\phi = 0$).

To solve the moral hazard problem, the compliance program uses random field inspections to observe compliance effort, and then punishes growers accordingly. Let α be the probability that the company audits a grower for compliance and let F be the per acre fine for noncomplying growers. The probability that a grower must pay the fine depends on the grower's compliance effort. A complying grower pays no fine, while a non-complying grower pays the fine F with probability α and pays nothing with probability $(1 - \alpha)$.

Given these definitions, a complying grower will buy Bt corn when a fine program is used if expected utility when complying equals or exceeds expected utility for conventional corn:

$$\text{(2)} \qquad \mathrm{E}[U(\pi_{cp} - (1 - \phi_c)T)] \geq \mathrm{E}[U(\pi_{cv})].$$

Condition (2) is the participation constraint for a company designing a fine program. Growers for whom the constraint is not satisfied will not buy Bt corn, which the company must take into account when choosing the technology fee.

When a fine program is used, a grower buying Bt corn will comply if expected utility when complying equals or exceeds expected utility when planting all Bt corn and paying a fine F with probability α:

$$\text{(3)} \qquad \mathrm{E}[U(\pi_{cp} - (1 - \phi_c)T)] \geq (1 - \alpha)\mathrm{E}[U(\pi_{bt} - T)] + \alpha\mathrm{E}[U(\pi_{bt} - T - F)].$$

Condition (3) is the incentive compatibility constraint for a company designing a fine program. Growers who buy Bt corn and for whom the constraint is not satisfied will not comply with the refuge requirement, but plant all Bt corn and pay the fine if audited. The company must take such optimal behavior into account when choosing the technology fee and designing the compliance program.

Constraint Reformulation

Examining the willingness to pay definition in equation (1) and participation condition (2) indicates that the participation condition can be expressed in terms of W as:

(4) $$W \geq (1 - \phi_c)T.$$

Using $G(W)$, the common knowledge distribution function for grower willingness to pay, this participation constraint can be expressed as a probability. Specifically, condition (4) implies that the probability any given complying grower will buy Bt corn is $\beta = \Pr(W \geq ((1 - \phi_c)T)$, or

(5) $$\beta = 1 - G((1 - \phi_c)T).$$

Equation (5) indicates that participation by complying growers does not depend on α or F and, regardless of the grower utility function and the distribution of grower willingness to pay, β is non-incresaing in the price T, since $\partial\beta / \partial T = -g((1-\phi_c)T)(1-\phi_c) \leq 0$, where $g(\cdot) \geq 0$ is the density function for $G(\cdot)$. That participation by complying growers decreases in the technology fee T is not surprising since it is the price of Bt corn.

Incentive compatibility condition (3) cannot be expressed explicitly in terms of W without further assumptions concerning grower utility. Nevertheless, a condition similar to the reformulation of the participation condition (4) exists.

PROPOSITION 1. *If grower utility is continuous and strictly increases in income, the incentive compatibility condition can be expressed as* $W \geq Z(\alpha, F, T)$, *where* $Z(\cdot)$ *is a general function depending on the grower utility function.*

Proof. See appendix.

Using $G(W)$, this incentive compatibility condition can be expressed as a probability that any given grower will comply with the refuge requirement when the company uses a fine program. Specifically, $\nu = \Pr(W \geq Z(\alpha, L, T))$, or

$$(6) \qquad \nu = 1 - G(Z(\alpha, L, T)).$$

Corollary 1. *The probability of compliance* ν *is non-decreasing in the audit probability* α *and in the fine* F *and is non-decreasing (non-increasing) in the technology fee* T *if*

$$(1 - \alpha)\mathrm{E}[U'(\pi_{bt} - T)] + \alpha\mathrm{E}[U'(\pi_{bt} - T - F)] - (1 - \phi)\mathrm{E}[U'(\pi_{bt} - T - \phi_c(py\lambda - T)] > (<)\ 0.$$

Proof. See appendix.

That both the audit probability and the fine increase the probability of compliance is not surprising, since both increase the cost of cheating and do not affect the cost of compliance. The ambiguity of the effect of the technology fee on the probability of compliance occurs because it increases both the cost of cheating and of compliance. The condition determining the sign uses the marginal change in grower utility to measure the effect of the technology fee on the cost of cheating and of compliance. The first two terms are the expected marginal increase in the cost of cheating and the last term is the expected marginal increase in the cost of complying. If the condition is positive (negative), the rate of increase of the cost of cheating when the technology fee increases is greater (less) than the rate of increase of the cost of complying, and so increasing the technology fee increases (decreases) the probability of compliance.

If participation condition (4) defines a lower bound on W that exceeds the lower bound defined by the incentive compatibility condition in Proposition 1, then $\beta > \nu$, otherwise $\nu \geq \beta$. Using the participation and incentive compatibility conditions, another condition can be derived that indicates whether $\beta > \nu$ or $\nu \geq \beta$. If condition (7) is satisfied, then $\beta > \nu$, otherwise $\nu \geq \beta$:

$$(7) \qquad (1 - \phi_c)T < Z(\alpha, F, T).$$

When $\beta > \nu$, a range for W exists over which growers will buy Bt corn and not comply. In this case, the probability that a grower buys Bt corn and complies is ν, while the probability that a grower buys Bt corn and does not comply is $\beta - \nu$. When $\nu \geq \beta$, all growers who buy Bt corn will comply. In this case, the probability that a grower buys Bt corn and complies is β, while the probability that a grower buys Bt corn and does not comply is zero. The company chooses the audit rate α, the fine F, and the price T, which together determine the probabilities β and ν, so that the company chooses expected grower participation and non-compliance. How the company chooses to tradeoff participation and compliance to determine optimal participation and non-compliance depends on its objective function.

Company Objective

The company maximizes net expected per acre returns from selling Bt corn to each farmer. Relative to selling only conventional corn, when selling Bt corn using a fine program, the company earns additional revenue from charging more for Bt corn and from collecting fines. Additional costs include any extra costs for producing Bt corn, the cost the monitoring compliance, and the cost of insect resistance to the Bt toxin if it develops. The applicable company objective depends on whether $\beta > \nu$. If condition (7) is satisfied, $\beta > \nu$ and the company's additional net expected per acre return is

$$V = (\beta - \nu\phi_c)(T - c) + (\beta - \nu)\alpha F - \beta k(\alpha) - (\beta\theta_c + (\beta - \nu)^2\theta_n)M, \tag{8}$$

which is the sum of expected net revenue from sales and collected fines, minus the expected costs of monitoring and from the development of resistance.

To focus on the participation and compliance issues the company faces, we assume a constant marginal cost c for each acre of Bt corn the company sells, so that company's net per acre revenue is $T - c$. The probability that any given grower will buy Bt corn and comply is ν, in which case the company's net per acre revenue is $(1 - \phi_c)(T - c)$, since the complying grower only plants the proportion $(1 - \phi_c)$ of fields in Bt corn. The probability that any given grower will buy Bt corn and not comply is $\beta - \nu$, in which case net per acre revenue is $(T - c)$. Hence, the expected net per acre revenue is $(\beta - \nu\phi_c)(T - c)$, the first term in equation (8).

For each grower, the probability that the company collects a fine is $(\beta - \nu)\alpha$, since with probability $(\beta - \nu)$ the grower does not comply and with probability α the grower is audited for compliance. Hence the expected per acre fine collected by the company is $(\beta - \nu)\alpha F$, the second term in equation (8). The company's per acre cost of monitoring compliance is $k(\alpha)$, where $k'(\cdot) > 0$ and $k''(\cdot) > 0$. The probability that a given grower will buy Bt corn is β, so that the company's expected monitoring cost is $\beta k(\alpha)$, the third term in equation (8).

The last term in equation (8), $(\beta\theta_c + (\beta - \nu)^2\theta_n)M$, is the company's expected per acre cost from the development resistance. If the ECB evolves resistance, the company will pay additional costs as a result of lost sales, lawsuits, fines, mitigation costs, and similar. Eventually ECB will evolve resistance to Bt corn, but when is uncertain because the complex process depends on many parameters with unknown values and is influenced by several stochastic factors (Hurley, Babcock, and Hellmich). Currently, a viable resistant population has not been detected in the field (Fox; Tabashnik et al.), but once such a population develops and is detected, the prevalence of resistance among the ECB population will increase quickly and field failures occur (Hurley, Babcock, and Hellmich). Therefore, we assume resistance is a binary event—either it has developed or it has not, and the company treats the development of resistance in any given year as a random event.

Resistance is an aggregate phenomenon, while this model uses a per acre basis. However, since $G(W)$ describes the distribution of willingness to pay among growers, the probability β is not only the probability that any given grower purchases Bt corn, but also the respective proportion of the grower population that purchases Bt corn. Similarly, ν is not only the probability that any given grower will comply, but also the proportion of the grower population that will comply. We assume the aggregate probability that resistance occurs increases proportionally with the total amount of Bt corn planted (β) and increases quadratically with the total amount of grower non-compliance ($\beta - \nu$), since non-compliance substantially increases the likelihood of resistance (Hurley, Babcock, and Hellmich). The parameters $\theta_c > 0$ and $\theta_n > \theta_c$ convert these aggregate probabilities to a per acre basis. Lastly, the cost to the company if resistance develops, after converting to a per acre basis, is $M > 0$, so that the expected per acre cost of resistance is $(\beta\theta_c + (\beta - \nu)^2\theta_n)M$.

If condition (7) is not satisfied for the α, F and T that maximize equation (8), then $\nu \geq \beta$ and the company's additional net expected per acre return is instead

$$V = \beta(1 - \phi_c)(T - c) - \beta k(\alpha) - \beta\theta_c M. \qquad (9)$$

When $\nu \geq \beta$, all growers who buy Bt corn will comply, so that the probability that a grower will buy and comply is β. Thus expected net sales revenue is $\beta(1 - \phi_c)(T - c)$, since the grower buys Bt corn with probability β and pays an additional $(1 - \phi_c)T$ because Bt corn is only planted on the proportion $(1 - \phi_c)$ of all corn acres. The company must still monitor compliance, otherwise the incentive compatibility condition and the compliance probability ν will change. Thus the expected cost of monitoring is $\beta k(\alpha)$, though no fines are collected, since all growers comply. Also, because all growers comply, the expected per acre cost of resistance reduces to $\beta\theta_c M$.

Because the probability $\beta = 1 - G((1 - \phi_c)T)$, the first order condition for maximizing equation (9) with respect to α reduces to $k'(\alpha) = 0$, which defines the optimal α independent of grower utility and the distribution of grower willingness to pay. The first order condition for maximizing equation (9) with respect to T can be expressed as $\beta - g((1 - \phi_c)T)[(1 - \phi_c)(T - c) - k(\alpha) - \theta_c M] = 0$, which defines the optimal T independent of grower utility. Because no fines are collected, equation (9) does not depend on the fine F. However, to ensure that the incentive compatibility condition is satisfied, the company must still conduct compliance audits and credibly threaten to impose a fine. Condition (7) and the α and T that maximize equation (9) define a lower bound for this fine F.

An interesting case for comparison to this optimal fine-based program is the company's optimal behavior when no compliance program is used. In this case, the company sells Bt corn, but does not audit compliance or collect fines, though it still pays any costs for the development of resistance. Thus equations (8) and (9) still describe the company's objective, except that monitoring costs and fine revenue are zero, i.e. $k(\alpha) = F = 0$, so that the probability of compliance ν differs, and the only choice variable is the technology fee T.

Finding the optimal compliance program requires first maximizing equation (8) with respect to the audit rate α, the fine F, and the price T, where equations (5) and (6) respectively define β and ν. If these values for α, F, and T satisfy condition (7), then they define the optimal compliance program. Otherwise, the α and T that maximize equation (9) and the associated lower bound on F from condition (7) define the optimal compliance program. Conceptually this problem is solvable, but determining a specific solution requires specifying a grower utility function, the distribution $G(W)$ for grower willingness to pay, and the cost of monitoring $k(\alpha)$.

Special Cases

In this section, we examine two special cases—growers with risk neutral preferences and with constant absolute risk aversion. If growers are risk neutral, equation (1) implies $\mathrm{E}[\pi_{cp}] = W + \mathrm{E}[\pi_{cv}]$ and incentive compatibility condition (3) becomes $\mathrm{E}[\pi_{cp} - (1 - \phi_c)T] \geq (1 - \alpha)\mathrm{E}[\pi_{bt} - T] + \alpha\mathrm{E}[\pi_{bt} - T - F]$, which simplifies to $\mathrm{E}[\pi_{cp}] + \phi_c T \geq \mathrm{E}[\pi_{bt}] - \alpha F$. Substitute $\mathrm{E}[\pi_{cp}] = W + \mathrm{E}[\pi_{cv}]$ into this expression and rearrange to obtain $W \geq \mathrm{E}[\pi_{bt}] - \mathrm{E}[\pi_{cv}] - \phi_c T - \alpha F$. Lastly, because $\pi_{bt} = \pi_{cv} + py\lambda$, then $\mathrm{E}[\pi_{bt}] - \mathrm{E}[\pi_{cv}] = \mathrm{E}[py\lambda]$. Thus the incentive compatibility condition in terms of W for a risk neutral grower is

$$W \geq \mathrm{E}[py\lambda] - \phi_c T - \alpha F. \tag{10}$$

This explicit formulation of the incentive compatibility condition allows definitive results concerning the effect of the technology fee T on the probability of compliance ν, unlike Corollary 1. Specifically, condition (10) implies that the probability of compliance is non-decreasing in the technology fee, since $\partial\nu/\partial T = g(\cdot)\phi_c \geq 0$, which holds regardless of the distribution of grower willingness to pay.

Grower risk neutrality also simplifies determination of the optimal compliance program.

PROPOSITION 2. *If growers are risk neutral, $k'(\alpha) = 0$ defines the optimal audit rate α regardless of the distribution of grower willingness to pay.*

Proof. See appendix.

Thus grower risk neutrality also implies that equations (8) and (9) need only be optimized with respect to F and T, treating α as a parameter defined by $k'(\alpha) = 0$.

With constant absolute risk aversion, grower utility is $U(\pi) = 1 - \exp(-R\pi)$, where $R > 0$ is the coefficient of absolute risk aversion. Equation (1) becomes $\mathrm{E}[1 - \exp(-R\pi_{cp})\exp(RW)] =$

$E[1 - \exp(-R\pi_{cv})]$, which implies $E[\exp(-R\pi_{cp})] = E[\exp(-R\pi_{cv})]/\exp(RW)$. Condition (3) becomes $E[1 - \exp(-R\pi_{cp})\exp(R(1 - \phi_c)T)] \geq (1 - \alpha)E[1 - \exp(-R\pi_{bt})\exp(RT)] + \alpha E[1 - \exp(-R\pi_{bt})\exp(RT)\exp(RF)]$. Rearranging gives $E[\exp(-R\pi_{cp})]\exp(R(1 - \phi_c)T) \leq E[\exp(-R\pi_{bt})]\exp(RT)(1 - \alpha + \alpha\exp(RF))$. Substituting $E[\exp(-R\pi_{cp})] = E[\exp(-R\pi_{cv})]/\exp(RW)$ into this expression and rearranging gives the incentive compatibility condition in terms of W when grower have constant absolute risk aversion:

$$W \geq -\phi_c T + \{\ln(E[\exp(-R\pi_{cv})]) - \ln(E[\exp(-R\pi_{bt})]) - \ln(1 - \alpha + \alpha\exp(RF))\}/R. \tag{11}$$

This explicit formulation of the incentive compatibility condition also implies that the probability of compliance is non-decreasing in the technology fee, since ${}^{\partial v}\!/_{\partial T} = g(\cdot)\phi_c \geq 0$, which holds regardless of the distribution of grower willingness to pay. However, no results comparable to Proposition 2 are possible.

Empirical Modeling and Conclusion

To assess the practical application of this fine-based program compliance program, we will empirically parameterize the conceptual model. We will assume growers are risk neutral or have constant absolute risk aversion. Data from a farmer survey in Minnesota and Wisconsin are available to estimate the distribution of grower willingness to pay. Published models and historical adoption data will be used to develop estimates of the probability of resistance with and without compliance and the cost of resistance to companies (Hurley, Babcock, and Hellmich; Hurley, Mitchell, and Rice; Mitchell et al.). Preliminary analysis (not reported) indicates that this program may have practical applicability. However, the empirical results require more thorough evaluation to determine their validity before they can be summarized here.

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Appendix

Proof of Proposition 1. Rearranging equation (1) gives $\mathrm{E}[U(\pi_{cp} - W)] - \mathrm{E}[U(\pi_{cv})] = 0$. Rearranging condition (3) gives $\mathrm{E}[U(\pi_{cp} - (1 - \phi_c)T)] - (1 - \alpha)\mathrm{E}[U(\pi_{bt} - T)] - \alpha\mathrm{E}[U(\pi_{bt} - T - F)] \geq 0$. Adding the equations gives

(A1) $\mathrm{E}[U(\pi_{cp} - (1 - \phi_c)T)] - (1 - \alpha)\mathrm{E}[U(\pi_{bt} - T)] - \alpha\mathrm{E}[U(\pi_{bt} - T - F)] + \mathrm{E}[U(\pi_{cp} - W)] - \mathrm{E}[U(\pi_{cv})] \geq 0$,

which we denote $H(W, \alpha, F, T) \geq 0$. The Implicit Function Theorem (Chiang pp. 205-208) implies that condition (A1) as an equality defines a continuous implicit function $W = Z(\alpha, F, T)$ in the neighborhood of a point $(W_0, \alpha_0, F_0, T_0)$ satisfying equation (A1) and has continuous partial derivatives if $H(\cdot)$ has continuous partial derivatives with respect to W, α, F, and T and if at the point $(W_0, \alpha_0, F_0, T_0)$, the partial derivative with respect to W is not zero.

Using equation (A1), the partial derivatives are:

(A2) $\partial H / \partial W = \mathrm{E}[U'(\pi_{cp} - W)]$,

(A3) $\partial H / \partial \alpha = \mathrm{E}[U(\pi_{bt} - T)] - \mathrm{E}[U(\pi_{bt} - T - F)]$,

(A4) $\partial H / \partial F = \alpha\mathrm{E}[U'(\pi_{bt} - T - F)]$,

(A5) $\partial H / \partial T = (1 - \alpha)\mathrm{E}[U'(\pi_{bt} - T)] + \alpha\mathrm{E}[U'(\pi_{bt} - T - F)] - (1 - \phi)\mathrm{E}[U'(\pi_{bt} - T - \phi_c(py\lambda - T)]$.

The last term in (A5) follows by substituting $\pi_{cp} = \pi_{bt} - \phi_c py\lambda$ and rearranging. If utility is continuous and strictly increases in income, then partial derivatives (A2)-(A5) are continuous and $\partial H / \partial W > 0$, so that the Implicit Function Theorem applies and the implicit function $W = Z(\alpha, F, T)$ exists.

Proof of Corollary 1. Given $W = Z(\alpha, F, T)$, the partial derivatives $\partial W / \partial x = \partial Z / \partial x = -\dfrac{\partial H / \partial x}{\partial H / \partial W}$ and, from equation (6), $\partial \nu / \partial x = -\, g(Z(\cdot))\, \partial Z / \partial x$ for all $x \in \{\alpha, F, T\}$. Since $g(\cdot) \geq 0$ for all density functions, $\partial \nu / \partial x$ has the opposite sign of $\partial Z / \partial x$, and since $\partial H / \partial W > 0$, $\partial Z / \partial x$ has the opposite sign of $\partial H / \partial x$, $\partial \nu / \partial x$ has the same sign as $\partial H / \partial x$. If utility strictly increases in income, (A4) implies $\partial H / \partial F > 0$, so that $\partial \nu / \partial F > 0$, and, if in addition $F > 0$, (A3) implies $\partial H / \partial \alpha > 0$, so that $\partial \nu / \partial \alpha > 0$. The sign of $\partial \nu / \partial T$ is the same as the sign of (A5), the condition reported in the corollary, which has an ambiguous sign since all three terms in (A5) are positive.

Proof of Proposition 2.

By equation (5), $\partial \beta / \partial \alpha = \partial \beta / \partial F = 0$. By condition (10), $Z(\cdot) = \mathrm{E}[py\lambda] - \phi_c T - \alpha F$, so that $\partial \nu / \partial \alpha = F g(\cdot)$ and $\partial \nu / \partial F = \alpha g(\cdot)$. The first order condition for maximizing equation (8) with respect to F can be expressed as:

(A6) $$\alpha(\beta - \nu) - \partial \nu / \partial F\, [\phi_c(T - c) + \alpha F - 2(\beta - \nu)\theta_n M] = 0.$$

Using $\partial \nu / \partial F = \alpha g(\cdot)$, and rearranging gives:

(A7) $$[\phi_c(T - c) + \alpha F - 2(\beta - \nu)\theta_n M] = (\beta - \nu)/g(\cdot).$$

The first order condition for maximizing equation (8) with respect to α can be expressed as:

(A8) $$F(\beta - \nu) - \partial \nu / \partial \alpha\, [\phi_c(T - c) + \alpha F - 2(\beta - \nu)\theta_n M] - \beta k'(\alpha) = 0.$$

Substituting in both $\partial v / \partial \alpha = Fg(\cdot)$ and (A7) for the term in square brackets and simplifying gives $-\beta k'(\alpha) = 0$, which has the rejected trivial solution $\beta = 0$ (no growers buy Bt corn) and the reported solution, which is independent of the distribution $G(W)$:

(A9) $\qquad k'(\alpha) = 0.$

If α, F and T from maximizing equation (8) imply $(1 - \phi_c)T \geq Z(\alpha, F, T)$, equation (9) is the applicable company objective and the first order condition with respect to α is $-\beta k'(\alpha) = 0$. Thus in both cases, the optimal α is defined by (A9), which does not depend on the grower utility function or the distribution of grower willingness to pay.

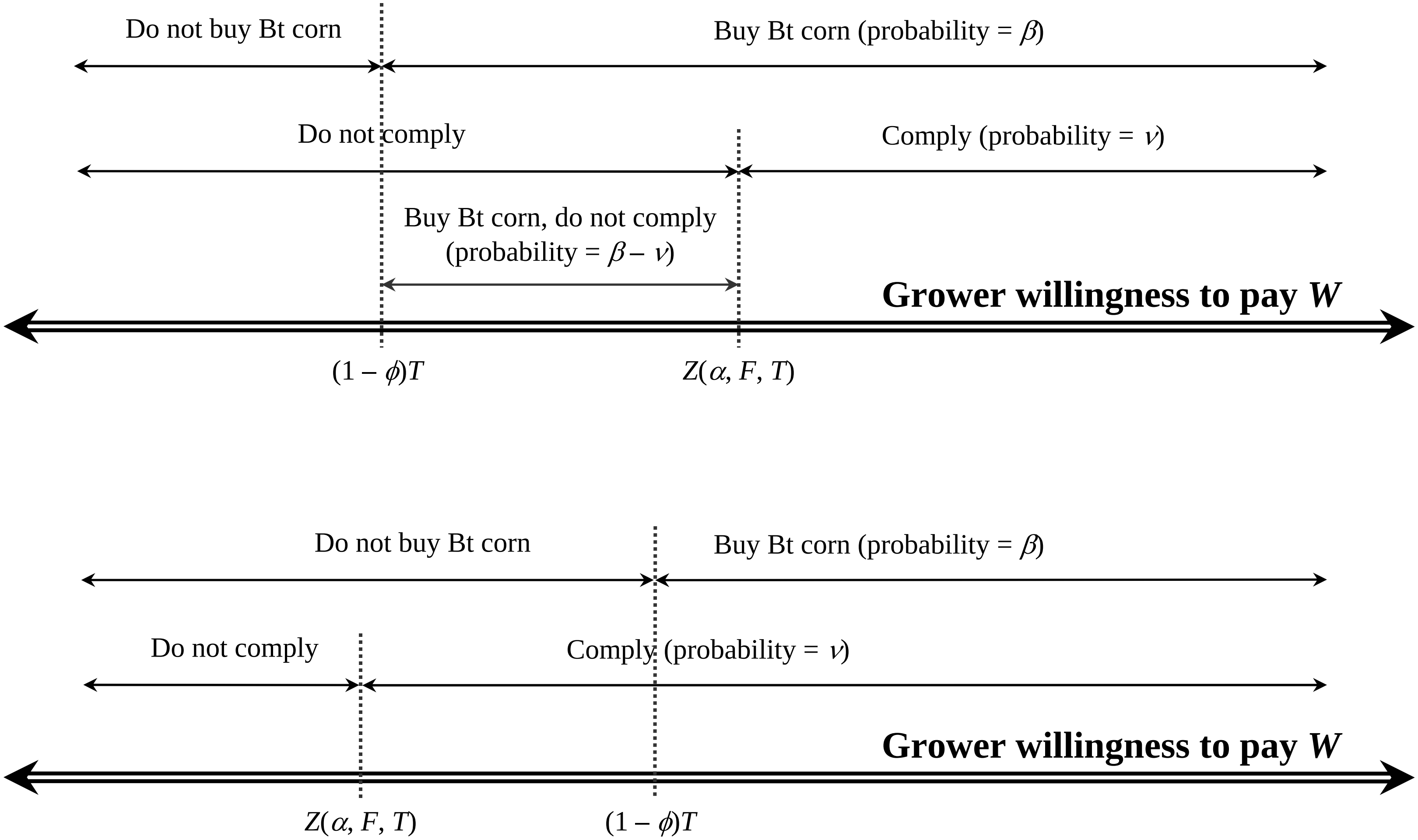

Figure 1. Illustration of the relationship between the threshold values defined by the participation and incentive compatibility constraints and associated optimal grower behavior over the range of grower willingness to pay for Bt corn.