Modeling Interdependent Participation Incentives: Dynamics of a Voluntary Livestock Disease Control Program

Tong Wang and David Hennessy

Working Paper 12-WP 527
April 2012

Center for Agricultural and Rural Development
Iowa State University
Ames, Iowa 50011-1070
www.card.iastate.edu

Tong Wang is a graduate assistant at the Center for Agricultural and Rural Development and a graduate student in the Department of Economics at Iowa State University.

David A. Hennessy is a professor of economics at Iowa State University.

For questions or comments about the contents of this paper, please contact Tong Wang, 71 Heady Hall, Iowa State University, Ames, IA 50011-1070; Ph: 515-294-8717; Fax: 515-294-6336; E-mail: wangtong@iastate.edu.

Partial funding for this study was provided by the United States Department of Agriculture, National Institute of Food and Agriculture under project title ‘Economics of the Food Supply Chain.’ Beyond funding, study sponsors had no involvement in any part of the study. We thank John Lawrence for encouraging the research.

Modeling Interdependent Participation Incentives: Dynamics of a Voluntary Livestock Disease Control Program*

Abstract: This paper models producers' interdependent incentives to participate in a voluntary livestock disease control program. Under strategic complementarity among participation decisions, after a slow start momentum can build such that market premium for participation and participation rate increase sequentially. Non-participation, partial participation and full participation can all be Nash equilibria while participation cost heterogeneity will dispose the outcome toward incomplete participation. We find plausible conditions under which temporary government subsidies to the least cost-effective producers causes tipping toward full participation. Applying parameters from the literature on Johnes' disease, we illustrate factors that may affect participation. These include cost heterogeneity and program effectiveness.

Keywords: Incentives, livestock disease, momentum theorem, strategic complementarity, tipping, voluntary program.

JEL classification: Q18, D83, L15

1. Introduction

Mandatory animal disease eradication programs have been a focus of government activity for more than a century. For example, the United States Department of Agriculture (USDA) campaign to eradicate the bovine tuberculosis (TB) between 1917 and 1940 was considered to have prevented at least 25,000 human TB deaths annually (Olmstead and Rhode 2004). While mandatory programs can be effective in bringing highly contagious diseases under control, staunch resistance to such mandates are common (Olmstead and Rhode 2007; Anderson 2010). As a result, voluntary control and certification programs have been promoted for several diseases. Examples include the Voluntary Trichinae Certification Program, the Chronic Wasting Disease Voluntary Herd Certification Program and the Voluntary Bovine Johne's Disease Control Program, all ongoing in the United States. The reward for being labeled as disease-free is a market-determined premium. For Johne's disease, survey results show that premiums exist for producers who participate in voluntary certification programs (Kovich, Wells and Friendshuh 2006; Benjamin et al. 2009).

The success of a voluntary program hinges on producer participation (CDCJD 2003). A natural question to ask is whether a voluntary control program provides producers with sufficient incentive to participate. Such a question has been addressed extensively in the environmental literature (Khanna 2001). At the individual firm level, it is generally assumed that voluntary programs involve lower implementation costs (Segerson and Miceli 1998); and that government subsidies provide firms with incentives to participate (Stranlund 1995; Wu and Babcock 1999). Participation incentives at an industry level have also been studied (Dawson and Segerson 2008; Millock and Salanie 2000). When multiple firms are involved and the government's aim is to reach a certain aggregate abatement level, some firms may have incentives to free ride on participation by other firms. We can view the firms' abatement decisions as strategic substitutes according to Bulow, Geanakoplos and Klemperer (1985). There is also an emerging literature on voluntary food safety programs where the incentive to participate is only analyzed at the individual firm level. The producer's incentive to join the voluntary program could come from the looming threat of a mandatory program (Fares and Rouviere 2010) or from government subsidies.

Extant analyses of voluntary programs tend to omit the interrelated nature of participation incentives. Even among studies that do consider firm interactions, interdependence in participation incentives is only studied in a static framework. In reality, however, almost all voluntary programs span multiple years, with evolving participation rates. Therefore, to evaluate firm participation incentives it is important to consider dynamic interactions among participant choices. This paper provides a pilot work on the issue. We provide a dynamic model in the context of a voluntary livestock disease control program.

Critical to model mechanics is the dynamic evolution of the price premium for proven disease-free product. Our goal is to analyze producers' incentives to participate in a disease control program that involves a disease status test, and subsequent incentives to release test information in order to acquire any market premium. As such our paper is closely connected with the quality disclosure literature. Under two strict assumptions, namely that *i*) disclosure is costless and *ii*) producers have full information about their quality, earlier studies found that all producers will disclose except the one with the lowest possible quality type (Grossman and Hart 1980). The market solves the information problem through unraveling, in a manner that is the reverse of that encountered in Akerlof's lemons problem (Viscusi 1978).

When assumption *i*) is relaxed, models by Jovanovic (1982), and Levin, Peck and Ye (2005) have found that only high-quality types would disclose. Alternatively, Matthews and Postlewaite (1985), Farrell (1986) and Shavell (1994) relaxed assumption *ii*) by assuming that sellers originally do not have information on their products' quality. Sellers could incur a test cost to acquire this information, where it is costless to disclose once acquired. They show that under voluntary disclosure sellers of the low cost type would acquire such information, and then disclose whenever it is favorable. A mandatory disclosure rule in this case would decrease the sellers' incentive to acquire the quality information in the first place.

Our model is based on Shavell (1994), where producers make two choices. These are a) whether to participate in the program to obtain quality information and possibly improve their quality, and then, if obtained, b) whether to disclose such information. Whereas Shavell assumed voluntary participation while disclosure could be either voluntary or mandatory, in this paper we use mandatory participation as a benchmark for comparison while disclosure is always voluntary. We extend Shavell's model to a dynamic setup, where we show that the participation premium hinges on the participation rate over time. This allows us to prove that producer decisions are strategic complements. Therefore even if only very few producers have the incentive to participate initially, they might in turn provide the remaining producers with sufficient incentive to participate. This phenomenon is referred to as tipping. The reasoning here resembles that in Dixit (2003), who shows how a small group of enthusiasts could initiate a process that subsequently induces all to join a club. This observation is important in that it provides insights on how animal disease program managers can engineer more efficient equilibria through selective subsidies.

Schelling's concept of tipping has been generalized by Gladwell (2000) to a wide range of problems. Heal and Kunreuther (2005) have explored the matter in a general interdependent risk setup. Tipping can occur when there are two or more equilibria and the system displays sufficient increasing differences (Heal and Kunreuther 2010). In the present paper, increasing differences arise because when more firms participate then the change in payoff to a firm upon participating will increase, i.e., the premium from participation will increase.

The premium increase arises from the declining health status among the non-disclosing herds, who are comprised of *i*) non-participating producers, and *ii*) participating producers that prefer not to reveal herd disease status. Every period, the average disease-free rate among non-disclosing herds is Bayesian updated and it decreases when more producers participate. As a result, momentum will build where three events successively reinforce each other. These are a decrease in the average disease-free rate among non-disclosing herds, an increase in participation premium and an increase in participation rate as a rational market response to the change in premium.

The paper's layout is as follows. After reviewing historical examples of voluntary and mandatory programs, we study how producers' participation decisions interact in a voluntary program. To provide a benchmark comparison, we also investigate a mandatory program. Besides tipping and strategic complementarity issues, our paper addresses roles for mandates and targeted subsidy policies as well as implications of cost heterogeneity. To illustrate, a simulation analysis on a voluntary Johne's disease herd status program (VJDHSP) is carried out where the parameters are obtained from the current Johne's disease literature.

2. Examples of voluntary and mandatory programs

2.1. Voluntary Johne's disease herd status program (VJDHSP)

Johne's disease (JD) has a long incubation period and clinical signs are rarely seen before two years of age. It is highly prevalent in the United States. According to the National Animal Health Monitoring System (NAHMS) dairy survey study of 2007, 68.1% of U.S. dairy herds were infected with the causative bacterium, *Mycobacterium paratuberculosis* (Mptb) (USDA 2008). Although the weight of evidence presently suggests no direct link between JD and Crohn's disease in humans, there is less agreement about any role it may play (Friswell, Campbell and Rhodes 2010). Due to production losses and zoonotic concerns, Johne's disease has been prioritized for control in the United States (CDCJD 2003) and the VJDHSP was developed to certify paratuberculosis free herds. Three key components of the program are *i*) education, *ii*) management, and *iii*) herd testing and classification. The purpose of *iii*) is to publicly recognize participating producers if they so desire.

Many U.S. states have established programs similar to the national VJDHSP (USDA 2010a), where Minnesota's program (MNJDCP) is among the most successful. Starting from less than 0.9% in 1999, the program's dairy herd participation rate had increased to 30.8% by the end of 2006, likely due in part to federal funding that commenced in 2003. Larger herds were more likely to participate than smaller herds. During 2005-'06, 52.9% of Minnesota dairy herds with ≥ 500 cows participated, in contrast with 9.9% among herds with < 50 cows (Wells, Hartmann and Anderson 2008). Meanwhile the program's beef herd participation rate had increased from less than 0.1% to 2.1%.

Benefits from participation include increased productivity and marketing opportunities (Kovich, Wells, and Friendshuh 2006; Benjamin et al. 2009). Also, as one program purpose is to provide a source of low-infection risk replacement cows (Kovich, Wells, and Friendshuh 2006), the industry would be well-prepared in the event that any link between Johne's disease in cattle and Crohn's disease were confirmed.

2.2. Texas fever

Texas tick fever was a major threat to the U.S. cattle industry from the Antebellum until the end of World War I. Efforts to eradicate tick carriers started as early as 1898, where initially participation had been voluntary. However it was soon recognized that eradication efforts would not succeed unless all cattle in a given area were treated, and so participation became mandatory in 1906.

Active resistance to the programs quickly emerged. Resistance was most intense among small-scale operators where per unit compliance costs were largest, leading to at least one 1922 murder in Arkansas (Hope 2005, pp. 10-12). As Strom (2000) notes, small farmer's "violent opposition to this program was founded in sound economic reasoning." However, larger ranchers began to see the benefit of eradication as sources for re-infection diminished, prospects for controlling residual infected areas increased, more areas were removed from federal quarantine and returns on treated animals increased. That is, a virtuous cycle of events led to a better equilibrium for those who could bear eradication costs. By 1933 Texas fever was no longer a major problem for the cattle industry (USDA 1933).

2.3. National animal identification system (NAIS)

NAIS is a U.S. government initiative launched in 2002 to establish a nationwide farm-level animal ID system to better manage disease outbreaks. The U.S. Animal Identification Plan (USAIP) was initially intended to be mandatory. In 2006 however, NAIS participation was made voluntary in the face of stiff opposition to compulsion. Approximately 36% of U.S. livestock premises had been registered by 2009. Participation rates in the premises registration step have been very high for poultry (95%), sheep (95%), high for swine (80%), but only 18% for cattle (Schnepf 2009).

Participation cost heterogeneity could explain the large differences in participation rates. According to NAIS (2009), the average per animal cost was \$0.0007/broiler, \$0.002/turkey, \$0.0195/layer, \$0.059/swine, \$1.39/sheep and \$5.97/bovine. The swine and poultry industries have much lower unit costs because animal tracing requirements for these species do not involve individual identification devices. Also, unit participation costs typically decrease with herd size; see, e.g., tables 2 and 3 of NAIS (2009).

The benefit from NAIS implementation increases as participation levels increase. According to simulation results in NAIS Benefit-Cost Research Team (2009), in the event of

Foot and Mouth disease outbreak "producer monetary losses for an animal identification and tracking program with a 90% participation rate would be \$4.5 billion less than a program with a 30% participation rate." For bovines this program was largely unsuccessful, due partly to failure by the USDA to communicate program benefits to producers (Anderson 2010).

3. Voluntary program

In a voluntary program, a producer makes his own decision on whether to participate based on participation benefits and costs. These benefits and costs evolve during the course of the program, and it is necessary to explicitly model the evolution of incentives.

3.1. Model scheme

Similar to Shavell (1994), we commence with a model of information acquisition and disclosure. In our context, information is referred to as knowledge on a herd's disease-free rate, i.e., the number of disease-free animals divided by the number of animals in the herd. In this paper we will analyze a situation where neither producers nor buyers know the precise quality of the good (Shavell 1994; Matthews and Postlewaite 1985). A third party provides tests as a part of the voluntary program to reveal the disease status to producers.

A herd's disease-free rate is denoted by $r \in [\underline{r}, 1]$ with distribution function $F(r)$. While $F(r)$ is common knowledge among all producers, a herd's particular *r* remains unknown prior to program participation.[1] Participation cost is denoted by $c \in [\underline{c}, \overline{c}]$ with distribution function $G(c)$. Each producer is only aware of his own participation cost. In Assumption 1, we will

[1] The current literature on animal disease generally assumes an asymmetric information structure, i.e., only producers have full information about their herd's disease status (Gramig, Horan, and Wolf 2009; Sheriff and Osgood 2010). However, producer knowledge about some chronic diseases can be very limited due to their long incubation periods.

define the relationship between the participation cost and disease-free rate.

Assumption 1: Herd participation costs are statistically independent of herd's disease-free rates.

Assumption 1 is supported by observations in Pillars et al. (2009), who conducted a 5-year longitudinal study of six Michigan dairy herds infected with JD. The data collected in their paper shows no pattern of correlation between disease prevalence rate and participation cost.

The model scheme is as follows. In period t, producers decide whether to participate based on the expected price premium realized in the previous period, I_{t-1}. Assume that producers participate whenever their expected price premium I_{t-1} is no less than the cost so that proportion $\eta_t = G(I_{t-1})$ of producers participate. Upon obtaining the test result, a participant will disclose whenever the result exceeds the average disease-free rate among silent producers in the previous period, r_{t-1}^S. Silent producers are comprised of two groups: producers 1) who choose not to participate in the program; and 2) who participate but prefer not to disclose any information. Here we assume that buyers cannot distinguish between the two groups. We also assume that there are many producers in the market and a single producer's participation decision cannot affect the overall market participation rate.

Based on participation and disclosure rates, an updated average disease status among silent producers in period t will be determined as r_t^S. In turn, a new price premium from participation will be solved as I_t. We will elaborate on the determination of I_t and r_t^S later. Note that except for the specified distributions on disease-free rate and participation cost, all other variables in the model scheme are endogenous. The process continues indefinitely through time where Figure 1 displays a model scheme. The price premium from participation will also depend on the information conveyed by the test results. We assume that the test reveals the exact disease-free rate to participating producers.[2]

3.2. Determination of participation premium

In period t testing reveals the exact disease-free rate, r, to the producer. The expected unit animal value for the herd with disease-free rate r is $rV+(1-r)\alpha V$. Here V and αV denote the values of healthy and diseased animals, respectively. Parameter α can vary by disease and indicates the perceived consequences. If buyers perceive no harm then $\alpha = 1$, but $\alpha < 1$ otherwise. Indeed one would expect $\alpha < 0$ whenever the disease causes serious human health problems, e.g., whenever the animal's produce can find no market. The average disease-free rate among silent producers is r_t^S. How equilibrium r_t^S is determined will be discussed shortly.

As non-participants belong to the group of silent producers, the unit livestock price of a non-participating herd is $p_t^1 = r_t^S V + (1-r_t^S)\alpha V$. A participant will reveal herd r whenever it is greater than r_t^S and will remain silent otherwise. Thus the realized price for a participating herd animal takes the form:

$$p_t^2 = \begin{cases} r_t^S V + (1-r_t^S)\alpha V, & \text{whenever } r \le r_t^S; \\ rV + (1-r)\alpha V, & \text{whenever } r > r_t^S. \end{cases} \tag{1}$$

The realized premium from participation is calculated as:

$$p_t^2 - p_t^1 = \begin{cases} 0, & \text{whenever } r \le r_t^S; \\ (1-\alpha)V(r-r_t^S), & \text{whenever } r > r_t^S. \end{cases} \tag{2}$$

The ex-ante expected price premium from participating in the program is:

$$I_t(r_t^S, \alpha, V) = (1-\alpha)V\int_{r_t^S}^{1}(r-r_t^S)\,dF(r), \tag{3}$$

[2] A second scenario, referred to as coarse grading, is studied in supplemental materials. It seeks to better replicate threshold rate classifications in actual programs.

leading to some comparative statics for the expected premium's trajectory.

Lemma 1: The expected premium from participation will increase whenever one of the following holds: *i*) Society becomes more aware of the disease, $\partial I_t / \partial \alpha \le 0$; *ii*) the value of an animal increases, $\partial I_t / \partial V \ge 0$, or *iii*) the average disease-free rate among silent producers decreases, $\partial I_t / \partial r_t^S \le 0$.

All nontrivial proofs are provided in Supplementary Materials (SM). From item *ii*) in Lemma 1 we learn that producers will have stronger incentives to participate whenever the unit livestock value increases. Therefore, when compared to dairy cow producers, beef cow producers have weaker incentives to participate as illustrated by the different participation rates in the MNJDCP. Item *iii*) conveys that the expected premium from participation will increase whenever the average disease-free rate among non-disclosing herds decreases. Intuitively, as the perceived mean quality in the unknown pool declines, buyers are willing to pay a larger premium to obtain livestock with a confirmed high disease-free rate. For the remainder of our formal analysis we will consider α and V to be fixed. To economize on notation we write $\gamma \equiv (1-\alpha)V$ and contract $I_t(r_t^S, \alpha, V)$ to $I_t(r_t^S, \gamma)$ or just $I_t(r_t^S)$.

3.3. Market equilibrium

The program commences in period 0. Initially $\eta_0 = 0$ as no producer participates. The average disease status among silent producers is the unconditional mean of r labeled as r^e, i.e., $r_0^S = r^e = \int_{\underline{r}}^1 r dF(r)$. By eqn. (3), the price premium in period 0 is:

$$I_0 = I(r_0^S) = \gamma \int_{r_0^S}^1 (r - r_0^S) dF(r). \tag{4}$$

According to the model scheme in Figure 1, in period 1 producers with participation costs no more than I_0 will participate. Thus the overall participation rate is $\eta_1 = G(I_0) = G(I(r_0^S))$. Among participants, those who obtain a disease-free rate less than r_0^S will not disclose any information on their disease status. This group has mass measure $\eta_1 F(r_0^S)$ with the average disease-free rate $r^e_{r \le r_0^S} \equiv E(r \mid r \le r_0^S)$. In addition, non-participants cannot disclose their disease-free rates. They have mass measure $1-\eta_1$ with the average disease-free rate r^e. The average disease-free rate among silent producers is Bayesian updated in period 1 as:

$$
\begin{aligned}
r_1^S(\eta_1) &= \begin{cases} \pi(\eta_1) r^e_{r \le r_0^S} + (1-\pi(\eta_1)) r^e & \text{whenever } \eta_1 < 1; \\ \underline{r}, & \text{whenever } \eta_1 = 1; \end{cases} \\
\pi(\eta_1) &= \frac{\eta_1 F(r_0^S)}{\eta_1 F(r_0^S) + 1 - \eta_1}.
\end{aligned} \tag{5}
$$

The denominator in the expression for $\pi(\eta_1)$ represents the proportion of silent producers among all producers, while the numerator represents the proportion of participants who choose not to disclose the result among all producers. After solving for r_1^S by way of (5), we can calculate the expected premium in period 1 as $I(r_1^S)$ by (4). Note that when $\eta_1 = 1$ then $r_1^S = \underline{r}$ and this is a rational expectations equilibrium.[3] When $\eta_1 < 1$ then (5) also presents a rational expectation for r_1^S on the part of buyers and so (5) supports internal consistency.

The process repeats in each period t, $t \in \{1, 2, \ldots\}$. Equilibrium will be reached at time t whenever some solution (η^*, r^*) is reached where $\eta_{t+1} = \eta_t = \eta^*$ and $r_{t+1}^S = r_t^S = r^*$. Similar to

[3] Were all producers to obtain their disease status information, then producers with a disease-free rate higher than the average will choose to disclose. The average disease-free rate among non-disclosers will continue to decrease until it reaches $\underline{r}$. Eventually all participants will disclose (Grossman and Hart 1980).

(5), the equilibrium condition is characterized by:

$$
\begin{aligned}
r^*(\eta^*) &= \begin{cases} \pi(\eta^*) r^e_{r \le r^*} + (1-\pi(\eta^*)) r^e & \text{whenever} \quad \eta^* < 1; \\ \underline{r} & \text{whenever} \quad \eta^* = 1; \end{cases} \\
\pi(\eta^*) &= \frac{\eta^* F(r^*)}{\eta^* F(r^*) + 1 - \eta^*}; \qquad \eta^* = G(I(r^*)).
\end{aligned} \tag{6}
$$

Were $\eta^* = 1$, then of course $r^* = \underline{r}$. In this case the full-participation (FP) equilibrium is reached, the pool of silent producers will disappear and the price premium becomes $I = I(\underline{r})$. Were $\eta^* = 0$, then $G(I(r^*)) = 0$, $r^* = r^e$ and $I = I(r^e)$. This characterizes the non-participation (NP) equilibrium. Lastly a partial-participation (PP) equilibrium is defined whenever $\eta^* \in (0,1)$, i.e., $G(I(r^*)) \in (0,1)$ and $r^* \in (\underline{r}, r^e)$.

The equilibrium condition in (6) was previously defined in Shavell (1994). However, Shavell did not recognize the need to redefine r^* at $\eta^* = 1$. In addition, our paper demonstrates dynamically how the equilibrium could be reached, a feature not captured in Shavell (1994). An understanding of the underlying dynamics is crucial because, as we will show, the complementary nature of participation decisions allows for multiple equilibria where tweaking the decision environment through policy interventions can tip equilibrium participation from very low to very high.

Presently, for the sake of illustrating the nature of equilibrium and the potential for policy interventions we focus on static Nash equilibrium solutions. Two thresholds used in this division are $I_{\min} = I(r^e)$ and $I_{\max} = I(\underline{r})$, which stand for the premium at NP and FP equilibria, respectively. In Figure 2 the horizontal and vertical axes represent possible values of $\underline{c}$ and $\overline{c}$, i.e., producers' lowest and the highest participation costs, respectively. As $\overline{c} \ge \underline{c}$, the region below the 45 degree line in Figure 2 is infeasible. The area above the diagonal line is divided into six regions. All Nash equilibria are provided in Figure 2, but we distinguish between two sorts of equilibria. Those not underlined are the ones that emerge with the default in initial point that no producers participate. Those underlined are ones that could be arrived at were the starting point to differ.[4]

In light of producer participation incentives, we consider six regions in two categories. The first category consists of Regions R2, R3, R5 and R6. Absent subsidy all the producers in this category will inevitably make the same participation decision. For R2, R3 and R5, $I_{\min} \le \underline{c} \le \overline{c}$, so NP is the equilibrium arrived at when no one participates initially. In contrast, region R6 with $\underline{c} \le \overline{c} < I_{\min}$ only displays the FP equilibrium. The second category covers only R1 and R4. Then, under no subsidy, equilibrium participation decisions based on no initial participation are less clear. Underlined equilibria for R2, R4 and R5 require different initial expectations.

We are particularly interested in region R4, with $\underline{c} < I_{\min} \le \overline{c} < I_{\max}$, and R5, with $I_{\min} \le \underline{c} \le \overline{c} < I_{\max}$. In these two regions if government entices (perhaps by cheap talk) a sufficiently large subset of producers to participate first, then FP could be maintained without any subsidy. In Lemma 2 we will show that at least two equilibria can indeed exist in R5. For region R4 a similar proof can be readily developed.

Lemma 2: Under a voluntary program, when $I_{\min} \le \underline{c} \le \overline{c} < I_{\max}$ then at least two equilibria exist. These are NP and FP.

Moving from NP or PP to FP, perhaps because of some market event or economic engineering, is referred to as tipping. Here we assume that the NP and PP equilibria are viewed by the government as undesirable equilibria when compared to FP equilibrium.

[4] To be more precise, it is what participants believe about the behavior of other producers that matters and not actual initial participation.

A last note on Figure 2 is that it also illustrates the effect of cost heterogeneity on equilibrium participation status. All points on the 45 degree line represent the case where minimum cost equals to the maximum cost, i.e., participation costs are homogenous among producers. In this case the equilibrium will be either FP or NP, depending on the cost level. By contrast, points further away from the 45 degree line denote cases where participation costs are more heterogeneous. Among regions, R1 has the most heterogeneous cost structure. In this region a proportion of lowest cost producers will always participate. However, FP cannot be reached unless the government consistently provides subsidies to the highest cost producers.

Take the cow-calf sector in the NAIS program for example. Due to its high average participation cost and cost heterogeneity (NAIS 2009), its cost structure is mostly likely located in either R1 or R2. Therefore FP is unlikely to be reached without a government subsidy. In contrast, poultry and swine sectors have much lower NAIS program participation costs together with nearly full participation rates, so we are almost certain that cost structures for those two sectors are located in R6. As participation cost scale economies exists, cost heterogeneity is most likely to exist in industries where large and small firms co-exist. In this case large producers tend to join the program first while small producers will most likely find it unprofitable to join the program without government subsidies, as with Minnesota's MNJDCP.

Note that Lemma 2 only shows two guaranteed equilibria. However, whenever FP and NP are two guaranteed equilibrium, a PP equilibrium may also be possible depending on the producer cost structure. This point will be illustrated in Example 1 below, which depicts a case of tipping in region R5 after the government motivates a subset of producers to participate.

Example 1 (Tipping): There are four participation costs, $(c^1, c^2, c^3, c^4) = (5.5, 5.7, 6.7, 8)$, and N producers with each. Here superscript is used to denote the cost type. Prior to participation, the disease-free rate of any herd is uniformly distributed on $[\underline{r}, \overline{r}] = [0.9, 1]$. The unit livestock value is $V = 500$, and $1-\alpha = 0.8$. First we establish:

$$I_{\min} = 500 \times 0.8 \int_{0.95}^{1} \frac{r-0.95}{1-0.9} dr = 5; \qquad I_{\max} = 500 \times 0.8 \int_{0.90}^{1} \frac{r-0.9}{1-0.9} dr = 20.$$

Thus $I_{\min} \le \underline{c} \le \overline{c} \le I_{\max}$. By Lemma 2, both NP and FP are equilibria. Next we illustrate how the NP equilibrium can be tipped to the FP equilibrium.

<u>Period 0</u>: We know that $r_0^S = r^e = 0.95$ so that the NP equilibrium will be reached without government intervention.

<u>Period 1</u>: Suppose now that in period 1 the government provides a one-time subsidy of 0.5 to producers of all cost types contingent on their participation. For type 1 producers the new cost will be reduced to 5. Thus 25% (as $N/4N = 0.25$) of producers will participate in period 1. Among participants, fraction $(0.95-0.9)/(1-0.9) = 0.5$ do not disclose. Therefore $\pi(\eta_1) = 0.25 \times 0.5/(0.25 \times 0.5 + 0.75) = 0.1429$. In period 1, average disease status among silent producers is: $r_1^S = \pi(\eta_1) r^e_{r \le r_0^S} + (1-\pi(\eta_1)) r^e = 0.1429 r^e_{r \le 0.95} + 0.8571 \times 0.95 = 0.9464$ and the expected premium is $I_1 \equiv I(r_1^S) = 4000 \int_{r_1^S}^{1} (r - r_1^S) dr = 5.75$ where 500(0.8)/(1-0.9)=4000.

<u>Period 2</u>: In this period producers of cost type 1 and 2 will participate <u>without</u> subsidy because $\max[c^1, c^2] < I_1$. Among participants, share $(0.9464-0.9)/(1-0.9) = 0.464$ will choose not to disclose their disease status. Thus $\pi(\eta_2) = 0.5 \times 0.464/(0.5 \times 0.464 + 0.5) =$ 0.3169. In period 2, the average disease status among silent producers is $r_2^S = \pi(\eta_2) r^e_{r \le r_1^S} +$ $(1-\pi(\eta_2)) r^e = 0.3169 r^e_{r \le 0.9464} + 0.6831 \times 0.95 = 0.9415$, and expected premium is $I_2 \equiv I(r_2^S)$ $= 4000 \int_{r_2^S}^{1} (r - r_2^S) dr = 6.84$.

<u>Period 3</u>: Given I_2, cost types 1, 2 and 3 producers will participate without subsidy.

Among participants, 41.5% will choose not to disclose their disease status. Thus $\pi(\eta_3) =$ $0.75 \times 0.415 / (0.75 \times 0.415 + 0.25) = 0.5546$. In period 3, the average disease status among silent producers is $r_3^S = \pi(\eta_3) r^e_{r \le r_2^S} + (1 - \pi(\eta_3)) r^e = 0.5546 r^e_{r \le 0.9415} + 0.4454 \times 0.95 = 0.9338$ and the expected premium is $I_3 \equiv I(r_3^S) = 4000 \int_{r_3^S}^{1} (r - r_3^S) dr = 8.76$.

Period 4: Given the value of I_3, all producers will participate without subsidy. In turn all producers will disclose, so $r_4^S = \underline{r} = 0.9$ and $I(r_4^S) = 20$. Therefore in period 5 and thereafter, all producers will participate. The FP equilibrium $(\eta^*, r^*) = (1, 0.9)$ is reached.

As an additional note on Lemma 2's conclusion, suppose instead that the type 2 cost producers exceeds 5.75 in the example. Then, as $I_1 = 5.75$, the tipping process will stall and only PP will be reached unless the government also provides a sufficient subsidy to types other than type 1. Therefore the PP equilibrium is also possible for region R5.

Following Definition 2 in Heal and Kunreuther (2010), type 1 producers in Example 1 form a critical coalition. This is because if cost type 1 producers participate then the NP equilibrium will switch to the FP equilibrium. In our example, by taking advantage of this critical coalition, government only provides a total subsidy payment of 0.5*N*. Without recognizing the existence of this group, and so providing subsidies to all to bring net costs down to 5, the government would pay a total subsidy of $(0.5 + 0.7 + 1.7 + 3)N = 5.9N$. An even more costly case is where all producers are provided the marginal subsidy required to elicit participation by type 4. Then cost is 12*N*, a 24-fold increase over the tipping solution.

The underlying reason for tipping in Example 1 is the strategic complementarity property among producer participation decisions, or 'increasing difference' (Heal and Kunreuther 2010). The producers' participation decisions are strategic complements if one producer's marginal payoff from participating increases whenever the participation rate increases, i.e., marginal returns to participation rise when more producers participate. Such a game is referred to as supermodular (Milgrom and Roberts 1990).

Here the expected marginal payoff from participating at time t is I_t. Therefore, the strategic complementarity property holds if whenever $0 \leq \eta_t' \leq \eta_t'' \leq 1$ then $I_t(r_t^S(\eta_t')) \leq I_t(r_t^S(\eta_t''))$. Next we will investigate whether this property is satisfied in the general model setup. This leads to our paper's main result; strategic complementarity among participation decisions. In order to show this we will establish that the participation rate will increase whenever the previous period's premium increases.

Lemma 3: Suppose that the expected price premium in period $t+1$ is weakly greater than that in period t. Then the participation rate in period $t+2$ will be greater than that in period $t+1$. That is, if $I_t'' \geq I_t'$, then $\eta_{t+1}(I_t'') \geq \eta_{t+1}(I_t')$.

This result follows immediately from relation $\eta_t = G(I_{t-1})$, where cost distribution function $G(\cdot)$ is non-decreasing. Next we will establish strategic complementarity, i.e., that the premium will increase whenever the participation rate in the same period increases.

Proposition 1: Producer participation decisions are strategic complements. That is, whenever $1 \geq \eta_t'' \geq \eta_t' \geq 0$ then $r_t^S(\eta_t') \geq r_t^S(\eta_t'')$ and $I_t(r_t^S(\eta_t'')) \geq I_t(r_t^S(\eta_t'))$.

It is worth noting that strategic complementarity alone cannot guarantee a high participation rate. According to a simulation result in NAIS (2009), the benefit from NAIS would increase if participation rates increase. However as producers are generally unaware of potential program benefits (Anderson 2010) the program is unlikely to be attractive at the outset, even among low-cost producers. As a result only a small fraction of producers are likely to participate, confirming the belief that participation generates little benefit. Such a vicious cycle repeats so that the program stalls at a low participation rate equilibrium.

We will refer to the participation rates when plotted against time as the participation curve. Next we will provide a plausible condition under which the participation rate will increase over time without any intervention. This means that the participation curve itself is upward sloping.

Assumption 2: Assume that $J(r^S) = \phi(r^S)(r^e - r^e_{r \le r^S})$ is decreasing in $r^S \in [\underline{r}, r^e]$, where $\phi(r^S) = g(r^S)F(r^S)/[g(r^S)F(r^S)+1-g(r^S)]$ denotes the proportion of participants among all silent producers and where $g(r^S) \equiv G(I(r^S))$.

Proposition 2, to follow, shows that Assumption 2 guarantees that $r_0^S \ge r_1^S \ge \cdots \ge r_k^S$ without any exogenous forces. This means that market interactions would ensure that the average disease-free rate among silent producers decreases monotonically over time. From Example 1, we can see that the average disease-free rate among the silent producers will strictly decrease conditional on types 1 having a participation cost below 5. This will generate momentum whereby the premium and participation rate both (weakly) increase over time.

The outcome $r_0^S \ge r_1^S \ge \cdots \ge r_k^S$ will generally apply when the easily computable uniform distribution is assumed on cost and disease rate distributions and value to be protected is not small. Supplemental materials provide a demonstration. Therefore we can be assured that Assumption 2 is plausible.

Proposition 2: Under Assumption 2, then over time the *i*) average disease-free rate among silent producers is non-increasing, i.e., $r_0^S \ge r_1^S \ge \cdots \ge r_k^S$; *ii*) participation premium is non-decreasing, i.e., $I_0 \le I_1 \le \cdots \le I_k$; *iii*) participation rate is non-decreasing, i.e., $\eta_0 \le \eta_1 \le \cdots \le \eta_k$.

Proposition 2 is similar to the Momentum Theorem of Milgrom, Qian and Roberts (1991). This asserts that once a system starts along a path of growth in core variables,[5] the process will continue indefinitely until some exogenous forces disturb the system. A steady increase in participation rates occurred over the years for MNJDCP (Wells, Hartmann and Anderson 2008) and also for the tick eradication program to control Texas fever.

3.4. Effect of program effectiveness on premium

To this point we have assumed that the program does not improve herd health status. Henceforth we refer to such a program as the *baseline* program. In contrast, a *technologically effective* program is one where the act of participation improves the initial disease-free rate. Let the disease-free rate change from r to $\lambda(r) \in [0,1]$, where $\lambda(r) \geq r, \forall r \in [0,1]$ and the inequality is strict on some interval. Define the average disease-free rate among the silent producers under the effective program as $\tilde{r}_t^S$, and that under the baseline program in period t as r_t^S. The corresponding premiums for the two programs are thus $\tilde{I}_t \equiv \tilde{I}(\tilde{r}_t^S)$ and $I_t \equiv I(r_t^S)$ respectively. In Lemma 4 we will compare those two premiums assuming that $\tilde{r}_t^S \leq r_t^S$ always holds. In Proposition 3 to follow we will show that Assumption 2 suffices to ensure $\tilde{r}_t^S \leq r_t^S$.

Lemma 4: If $\tilde{r}_t^S \leq r_t^S$, then $\tilde{I}_t > I_t$.

Next we will compare the price premium of the effective program with that of the baseline program for every period.

---

[5] Here core variables refer to the variables that are mutually complementary and are assumed to be central to the firm's activities.

Proposition 3: Compared to the baseline program, the effective program always generates a greater expected price premium whenever Assumption 2 holds. That is $\forall t \geq 1,\ \tilde{I}_t > I_t$.

4. Participation mandate

A mandatory program requires all producers to participate, but does not require disclosure. The incentive to voluntarily participate in mandatory programs is often overlooked. This is a pity because mandates are likely to be most unpopular and likely ineffective when the post-mandate equilibrium involves a large fraction of involuntary participants. In this section we will show that the premium reaches a maximum when a program is mandatory. Therefore a mandate creates the greatest incentive for producers to remain in the program, given the strategic complementarity among participation decisions. Stated differently, upon passage of time the mandate may turn some involuntary participants into voluntary ones.

We assume that there is no non-participant in the mandatory program. Again by Grossman and Hart (1980), the average disease-free rate among silent producers will be $\underline{r}$. So although disclosure is voluntary, universal disclosure is a natural by-product of the mandate. By (3) the expected participation premium is:

$$I_{\max} = \gamma \int_{\underline{r}}^{1} (r - \underline{r}) dF(r) \tag{7}$$

By Lemma 1, we know that $I_{\max} = \max_{r_t^S} I(r_t^S)$, where $r_t^S \in [\underline{r}, r^e]$ is defined in eqn. (5).

Therefore, the premium under a mandate will be no less than that under a voluntary program.

Two types of participants can exist in a mandatory program. Motivated type A participants incur a lower cost than the premium under full participation. They have ex-post incentives to participate. The remainder belong to unmotivated type B, who participate only when the government spends effort auditing and imposes a fine on non-participants. According to this definition, we present three possible equilibria as shown in Figure 3. These are when:

1. $\underline{c} \leq I_{\max} \leq \overline{c}$, as represented by area M1. There exist a mixture of motivated type A and unmotivated type B participants in the market. Participants with $c \in [\underline{c}, I_{\max})$ are motivated types while those with $c \in (I_{\max}, \overline{c}]$ are unmotivated types;
2. $\underline{c} \geq I_{\max}$, as represented by M2. The market is comprised solely of type B participants;
3. $\overline{c} \leq I_{\max}$, as represented by M3. The market is comprised solely of motivated types.

Note that region M3 in Figure 3 contains exactly regions R4, R5 and R6 in Figure 2. That is, only type A participants exist under the mandate whenever FP is an equilibrium in the voluntary program. This is because a participation mandate maximizes the incentive for producers to join. According to our calculations in Example 1, we know that this example will be located in region M3 under the mandate. Therefore the market is comprised solely of type A participants. No participant will deviate from participation even were the government to spend no effort on auditing. When the cost structure lies in region M1, which is most likely when cost structures vary widely (as in the U.S. beef sector) in reality, then opposition from some producers is inevitable. As documented earlier, Texas tick fever eradication and NAIS programs encountered resolute resistance during their implementation.

5. Simulation

In this section we use JD as an example for simulation purposes. One objective of this section is to understand whether the current participation rate will increase or stagnate in the long run. We also calculate the percentage of motivated type A participants under the alternative mandatory program. Similar to Example 1, we use uniform distributions to capture a producers' cost structure and herd disease-free rate. Model parameter values are based on the current literature on Johne's disease. We assume throughout that the average disease-free rate is uniformly distributed, or $r \sim U[\underline{r},1]$, as is the participation cost, or $c \sim U[\underline{c},\overline{c}]$.

5.1. Voluntary program

By (3), in the baseline program the expected premium in period t is calculated as:

$$I_t = I(r_t^S) = \gamma \int_{r_t^S}^{1} (r - r_t^S) dF(r) = \gamma \int_{r_t^S}^{1} \frac{r - r_t^S}{1-\underline{r}} dr = \frac{\gamma (1-r_t^S)^2}{2(1-\underline{r})}. \tag{8}$$

For simplicity, we choose a linear technology that satisfies the definition of a technologically effective program; $\lambda(r) = 0.5(1+r)$. This technology is appealing because it reflects decreasing marginal returns, i.e., the increase in disease-free rate is $0.5(1+r) - r = 0.5(1-r)$, which is decreasing in the value of r.

The period t expected premium in the technologically effective program is:

$$\begin{aligned}\tilde{I}_t = \tilde{I}(\tilde{r}_t^S) &= \gamma \int_{\lambda^{-1}(\tilde{r}_t^S)}^{1} \left[\lambda(r) - \tilde{r}_t^S\right] dF(r) = \frac{\gamma}{1-\underline{r}} \int_{2\tilde{r}_t^S - 1}^{1} (0.5r + 0.5 - \tilde{r}_t^S) dr \\ &= \frac{\gamma}{1-\underline{r}} (1 - \tilde{r}_t^S)^2.\end{aligned} \tag{9}$$

By (5), the disease-free rate among silent sellers in period $t+1$ is:

$$\begin{aligned} & r_{t+1}^S = \phi(r_t^S) r_{r \le r_t^S}^e + [1 - \phi(r_t^S)] r^e; \\ & \phi(r_t^S) = \frac{G(I_t) F(r_t^S)}{G(I_t) F(r_t^S) + 1 - G(I_t)}; \qquad G(I_t) = \frac{I_t - \underline{c}}{\overline{c} - \underline{c}}; \qquad F(r_t^S) = \frac{r_t^S - \underline{r}}{1 - \underline{r}}; \\ & r_{r \le r_t^S}^e = \int_{\underline{r}}^{r_t^S} \frac{r}{r_t^S - \underline{r}} dr = 0.5(r_t^S + \underline{r}); \qquad r^e = \int_{\underline{r}}^{1} \frac{r}{1-\underline{r}} dr = 0.5(1 + \underline{r}). \end{aligned} \tag{10}$$

From an initial value of $r_0 = r^e$ we calculate premium I_0 by either (8), when considering the baseline program, or (9), when considering the technologically effective program. Next when r_0 and I_0 are known, r_1 will be solved by use of (10). For $t \ge 1$, I_t and r_{t+1} can be computed in turn. Lastly, participation rate $G(I_t)$ can be obtained in each period given I_t.

5.2. Mandate

By (7), under the baseline program the expected premium from participation is $I_{\max}$ =

$\gamma(1-\underline{r})^{-1}\int_{\underline{r}}^{1}(r-\underline{r})dr = 0.5\gamma(1-\underline{r})$: and the fraction of motivated type A participants is

$G(0.5\gamma(1-\underline{r})) = [0.5\gamma(1-\underline{r}) - \underline{c}]/(\overline{c} - \underline{c})$.

5.3. Parameter values and period length

We use the simple average of quarterly prices for replacement milk cows weighted by state cow numbers to calculate replacement cow prices in 2006, 2007 and 2008 (USDA 2010b). For 2009 and 2010, we use the first quarter milk cow prices as provided by USDA: NASS. Our estimate of the value of a healthy dairy cow is just the simple average of prices over these five years, $V = \$1,696$. For cows infected with Johne's disease, the estimated slaughter value is assumed to be in the range 0-30% of the original value (Groenendaal and Galligan 2003). To be conservative we assume that $\alpha = 0$.

It is estimated that the average within-herd prevalence in the United States is about 5.5% (USDA 2005) so we set $r^e = 0.945$. As we assume that the herd disease-free rate is uniformly distributed on $[\underline{r},1]$, it follows that $r \sim U[0.89,1]$. The cost of the JD control program ranges from $5.79 to $81.07 per cow per year (Pillars et al. 2009), and we assume that the cost is uniformly distributed on [$5.79, $81.07].

According to USDA (2010a), pp. 21 to 22, a classification test must be implemented annually for the herd at levels 1 to 4 establish or maintain a classification level. For herds at levels 5 to 6, this test is required every two years. Therefore the program period as specified in the simulation model can be viewed as ranging between one and two years.

5.4. Results

Equations (8) and (10) generate the participation rates under the voluntary baseline program for the first 20 periods, as displayed in Figure 4. Under the voluntary program, the participation rate increases slightly in the beginning and then stabilizes at just below 30%. This suggests that the current VJDHSP is unlikely to attract the majority of producers. Under the mandate however 100% of participants are content. So the current voluntary program supports an equilibrium located in region R4 of Figure 2 while a mandate supports an equilibrium located in region M3 of Figure 3. Therefore both PP and FP are equilibria in the voluntary program. Later on we will illustrate how the PP equilibrium can be tipped into the FP equilibrium.

Sensitivity analysis in regard to $\underline{r}$, α and V are explored in the supplemental materials. We devote the remainder of this section to policy and allied considerations.

5.6. Subsidy and tipping

Suppose that the government provides temporary subsidies to a proportion of producers. These subsidies may eventually motivate all producers to participate in the voluntary program. Due to our momentum inference in Proposition 2, subsidies will no longer be necessary after a certain proportion of producers participate. We assume that $r \sim U[0.89,1]$, $c \sim U[\$5.79,\$81.07]$, $V =$ $\$1,696$ and $\alpha = 0$. The simulation is displayed in Figure 5.

The equilibrium without subsidy will be reached at around the 5th period, where 29% of producers participate and the price premium is \$27 for participation. In the 6th period, suppose the government provides subsidies to 30% of producers. Specifically, suppose the government provides a uniform subsidy of \$55 to all producers whose cost lies in the upper 30 percentile of the cost distribution, i.e., $c \sim U[\$58.47,\$81.07]$. Then their cost will fall below \$27 and it will become profitable for them to participate. So long as low cost participants do not believe that they would become eligible for subsidies were they to procrastinate then the timing of the subsidies will not affect their participation decision.

In reality, as the smaller producers are more likely to incur higher participation costs, government could provide subsidies to the 30% of producers that are smallest in scale once it is realized that the participation rate is leveling off. Then the participation rate will climb again and the new full participation equilibrium will be reached after another 13 periods. The FP equilibrium will generate a price premium of $85. Thus no producer in the FP equilibrium has the incentive to deviate from it even without a government subsidy. An alternative approach that could more quickly and more reliably secure a high participation rate would be to subsidize small producer participation right from the outset.

5.7. Cost heterogeneity

We compare $c \sim U[\$5.79, \$81.07]$ with a distribution that is a mean-preserving decrease in dispersion, $c \sim U[\$15.79, \$71.07]$. We also choose two different values for α, namely -0.5 and 0.3. We do this to show that the effects of cost heterogeneity can be dramatically altered by the perceived magnitude of damage. The resulting participation rates are displayed in Figures 6(a)-6(b). In the case of a less heterogeneous cost structure, the equilibrium participation rate is either close to 0% (i.e., NP) or 100% (i.e., FP), while a more heterogeneous cost structure results in the PP equilibrium. When the participation premium increases relative to cost and costs are less heterogeneous then FP will result. This simulation result conforms to our observations based on Figure 2.

5.8. Program effectiveness

From equations (9)-(10) we obtain participation rates under the technologically effective program for the first 20 periods. Compared to the baseline program, the effect of program effectiveness on participation is displayed in Figure 7. When the program is effective in increasing the herd-level disease-free rate, the participation rate will increase in every period. The equilibrium participation rate will also increase. In our case FP is reached under the effective program. Intuitively, this is because if the program proves to be more effective then sellers can expect to obtain a larger price premium which will strengthen participation incentives among sellers.

6. Conclusion

With specific reference to animal disease, this paper provides a dynamic, industry-level model of a voluntary program where positive participation externalities exist. We show that, due to strategic complementarity, momentum builds whereby both premium and participation rate increase iteratively in a mutually reinforcing manner and may in time support full participation even without government subsidies. This is in contrast with much of the current literature on infectious animal disease management programs, which implicitly assumes that incentives for voluntary participation come either from direct productivity effects or government subsidies.

Secondly, we show that the participation premium and participation rate are contingent on disease consequences to human health, disease prevalence rate and unit livestock value. For example, if consumers perceive a serious human health consequence then a full participation equilibrium can be more readily attained.

We point out that, due to strategic complementarity, a program mandate maximizes the price premium and thus the incentive to participate. The private benefits to participation will be larger when calculated after the mandate is implemented. As our historical review attests, many initially hostile to a mandate may think differently afterwards. Theoretically, a sticks approach can dominates a carrots approach in regard to participation incentives. However enforcing the mandate might be difficult at the outset, and when heterogeneity in implementation cost is large then many producers may never benefit from the mandate. A voluntary program with modest government subsidies might be welcome by all producers, perhaps in part because of the positive publicity generated (Lyon 2003). Subsidies would also place some of the costs on taxpayers/consumers, who may be content to pay for greater confidence in the food supply chain. A voluntary approach may also afford producers with sufficient time to appreciate program benefits and initiate a virtuous cycle at low political cost.

Finally, as demonstrated in the application to Johne’s disease, our theoretical model can also be tailored for simulation purposes. This allows us to predict under given situations how the program participation rate may evolve over time, a feature that has not been explored in the existing literature. Our simulation results indicate that full participation is unlikely under the status quo. We also illustrate the process of tipping in the simulation, where the government could secure a FP equilibrium by subsidizing high cost producers. Therefore the success and cost effectiveness of a voluntary Johne’s disease control program, or of livestock disease control programs in general, hinges crucially on obtaining the right statistics as well as educating producers and consumers.

References

Anderson, D.P. 2010. “The U.S. animal identification experience.” *Journal of Agricultural and Applied Economics* 42(3):543-550.

Benjamin, L.A., G.T. Fosgate, M.P. Ward, A.J. Roussel, R.A. Feagin, and A.L. Schwartz. 2009. “Benefits of obtaining test-negative level 4 classification for beef producers in the Voluntary Bovine Johne’s Disease Control Program.” *Preventive Veterinary Medicine* 91(2-4):280-284.

Bulow, J., J. Geanakoplos, and P. Klemperer. 1985. "Multimarket oligopoly: Strategic substitutes and strategic complements." *Journal of Political Economy* 93(3):488-511.

Committee on Diagnosis and Control of Johne's Disease (CDCJD), Board on Agriculture and Natural Resources. 2003. *Diagnosis and Control of Johne's Disease.* Washington, DC: The National Academies Press.

Dawson, N.L., and K. Segerson 2008. "Voluntary agreements with industries: Participation incentives with industry-wide targets." *Land Economics* 84(1):97-114.

Dixit, A.K. 2003. "Clubs with entrapment." *American Economic Review* 93(5):1824-1829.

Fares, M., and E. Rouviere E. 2010. "The implementation mechanisms of voluntary food safety systems." *Food Policy* 35(5):412-418.

Farrell, J. 1986. "Voluntary disclosure: Robustness of the unravelling result, and comments on its importance." In R. Grieson. ed. *Antitrust and Regulation.* Lexington, MA: Lexington Books, 1-20.

Friswell, M., B. Campbell, and J. Rhodes. 2010. "The role of the pathogenesis of inflammatory bowel disease." *Gut and Liver* 4(3):295-306.

Gladwell M. 2000. *The Tipping Point: How Little Things Can Make a Big Difference.* New York, NY: Little, Brown and Company.

Gramig, B.M., R.D. Horan, and C.A. Wolf. 2009. "Livestock disease indemnity design when moral hazard is followed by adverse selection." *American Journal of Agricultural Economics* 91(3):627-641.

Groenendaal, H., and D.T. Galligan. 2003. "Economic consequences of control programs for paratuberculosis in midsize dairy farms in the United States." *Journal of American Veterinary Medical Association* 223(12):1757-1763.

Grossman, S.J., and O.D. Hart. 1980. "Disclosure laws and takeover bids." *Journal of Finance* 35(2):323-334.

Heal, G., and H. Kunreuther 2005. “IDS models of airline security.” *Journal of Conflict Resolution* 49(2):201-217.

Heal, G., and H. Kunreuther. 2010. “Social reinforcement: Cascades, entrapment, and tipping.” *American Economic Journal: Microeconomics* 2(1):86-99.

Hope, H. 2005. “Dip that tick: Texas Tick Fever eradication in Arkansas, 1907-1943.” Arkansas Historica Preservation Program, Little Rock, AR.

Jovanovic, B. 1982. “Truthful disclosure of information.” *Bell Journal of Economics* 13(1):36-44.

Khanna, M. 2001. “Non-mandatory approaches to environmental protection.” *Journal of Economic Surveys* 15(3):291-324.

Kovich, D.A., S.J. Wells, and K. Friendshuh. 2006. “Evaluation of the Voluntary Johne's Disease Herd Status Program as a source of replacement cattle.” *Journal of Dairy Science* 89(9):3466-3470.

Levin, D., J. Peck, and L. Ye. 2009. “Quality disclosure and competition.” *Journal of Industrial Economics* 57(1):167-196.

Lyon, T.P. 2003. “Voluntary versus mandatory approaches to climate change mitigation.” Issue Brief 03-01, Washington DC: Resources for the Future, February.

Matthews, S., and A. Postlewaite. 1985. “Quality testing and disclosure.” *Rand Journal of Economics* 16(3):328-340.

Milgrom, P., and J. Roberts. 1990. “Rationalizability, learning, and equilibrium in games with strategic complementarities.” *Econometrica* 58(6):1255-1277.

Milgrom, P., Y. Qian, and J. Roberts. 1991. “Complementarities, momentum, and the evolution of modern manufacturing.” *American Economic Review, Papers and Proceedings* 81(2):84-88.

Millock, K., and F. Salanie. 2000. “Collective environmental agreements: An analysis of the problems of free-riding and collusion." Fondazione Eni Enrico Mattei Working Paper 108-2000, Milan.

NAIS Benefit-Cost Research Team. 2009. *Overview Report of the Benefit-Cost Analysis of the National Animal Identification System.* Kansas State University. Available at: http://www.aphis.usda.gov/traceability/downloads/Benefit_Cost_Analysis.pdf, visited on 2/21/2012.

Olmstead, A.L., and P.W. Rhode. 2004. "An impossible undertaking: The eradication of Bovine Tuberculosis in the United States." *Journal of Economic History* 64(3):1-35.

Olmstead, A.L., and P.W. Rhode. 2007. "Not on my farm! Resistance to Bovine Tuberculosis eradication in the United States." *Journal of Economic History* 67(3):768-809.

Pillars, R.B., D.L. Grooms, C.A. Wolf, and J.B. Kaneene. 2009. "Economic evaluation of Johne's Disease control programs implemented on six Michigan dairy farms." *Preventive Veterinary Medicine* 90(3-4):223-232.

Schnepf, R. 2009. "Animal identification: Overview and issues." Congressional Research Service 7-5700, September.

Segerson, K., and T.J. Miceli. 1998. "Voluntary environmental agreements: Good or bad news for environmental protection?" *Journal of Environmental Economics and Management* 36(2):109-130.

Shavell, S. 1994. "Acquisition and disclosure of information prior to sale." *RAND Journal of Economics* 25(1):20-36.

Sheriff, G., and D. Osgood 2010. "Disease forecasts and livestock health disclosure: A shepherd's dilemma." *American Journal of Agricultural Economics* 92(3):776-788.

Stranlund, J. 1995. "Public mechanisms to support compliance to an environmental norm." *Journal of Environmental Economics and Management* 28(2):205-222.

Strom, C. 2000. "Texas Fever and the dispossession of the Southern yeoman farmer." *The*

Journal of Southern History 66(1):49-74.

U.S. Department of Agriculture (USDA). 1933. *Yearbook of Agriculture, 1933.* Washington, DC.

——. 2005. *Johne's Disease on U.S. Dairy Operations, 2002.* NAHMS USDA: APHIS:VS:CEAH, Fort Collins. CO, USA. N427.0205.

——. 2008. *Johne's Disease on US Dairies, 1991-2007.* NAHMS USDA: APHIS:VS:CEAH, Fort Collins. CO, USA, #N521.0408.

——. 2010a. *Uniform Program Standards for the Voluntary Bovine Johne's Disease Control Program.* APHIS 91-45-016.

——. 2010b. *Agricultural Statistics 2010.* National Agricultural Statistics Service.

Viscusi, W.K. 1978. "A note on 'lemons' markets with quality certification." *Bell Journal of Economics* 9(1):277-279.

Wells, S.J., W.L. Hartmann, and P.L. Anderson. 2008. "Evaluation of progress made by dairy and beef herds enrolled in the Minnesota Johne's Disease Control Program." *Journal of the American Veterinary Medical Association* 233(12):1920-1926.

Wu, J., and B.A. Babcock. 1999. "The relative efficiency of voluntary vs. mandatory environmental regulations." *Journal of Environmental Economics and Management* 38(2):158-175.

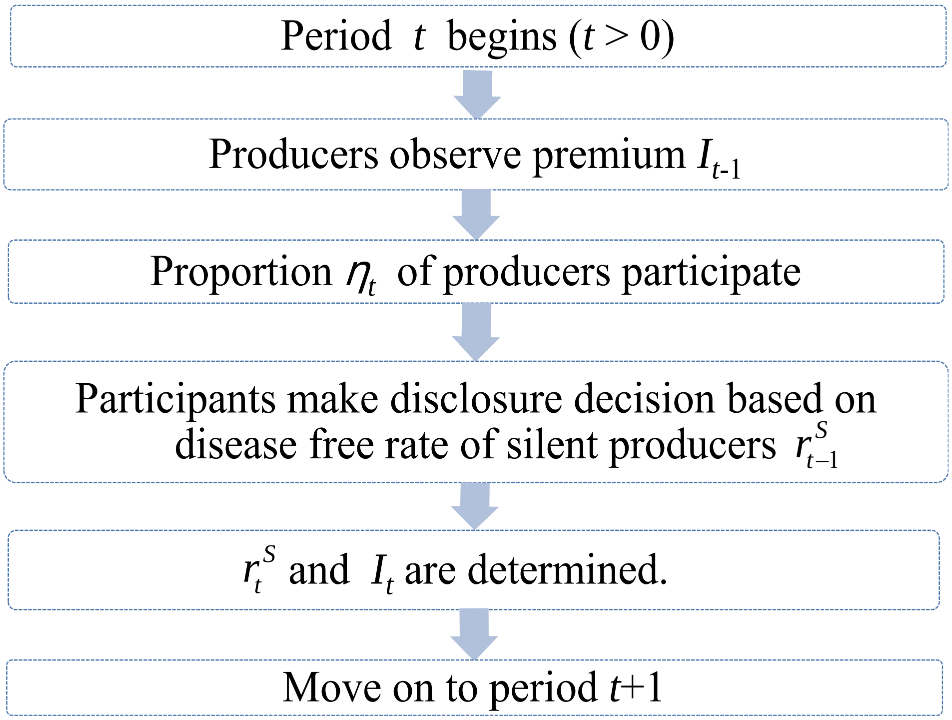

Figure 1. A flow chart of the model scheme.

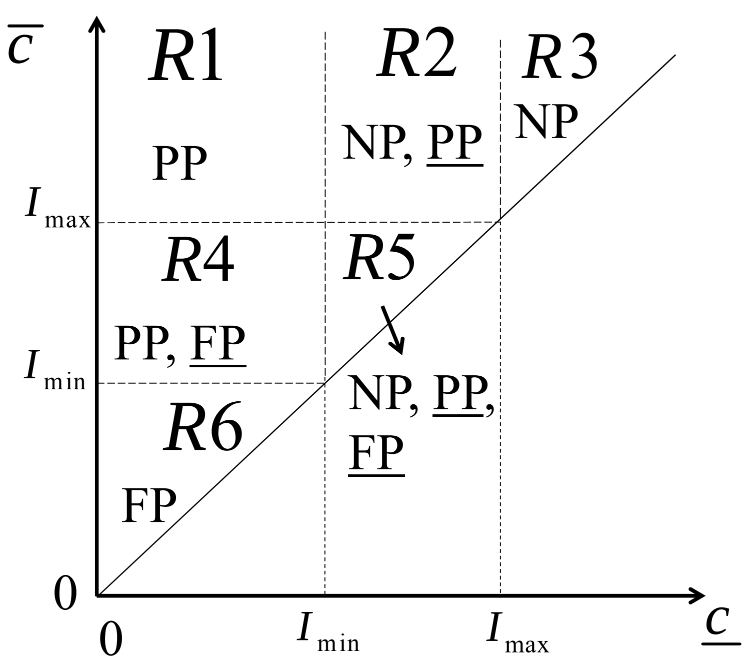

Figure 2. Equilibria under different cost structures—voluntary program.

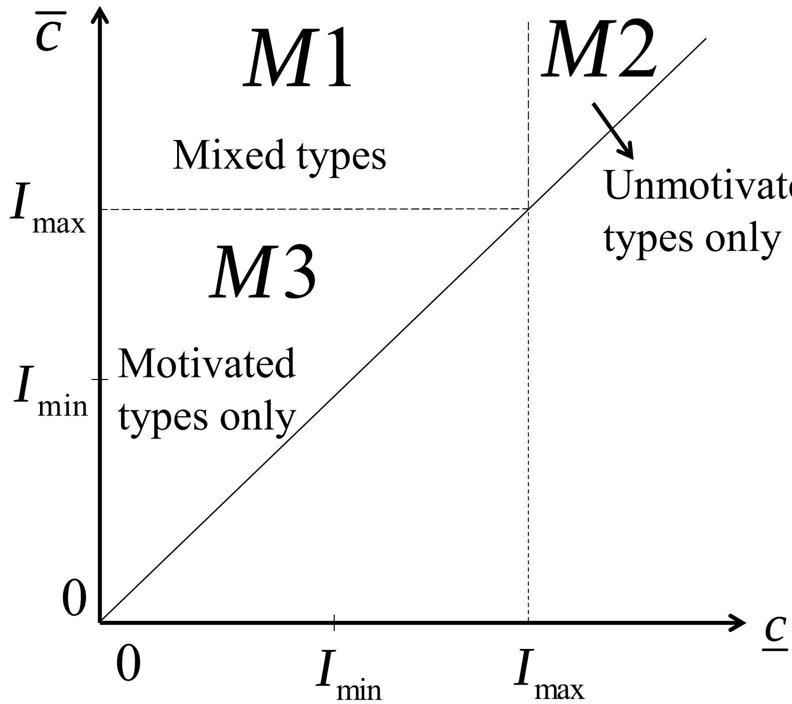

Figure 3. Participant types under different costs—mandatory program.

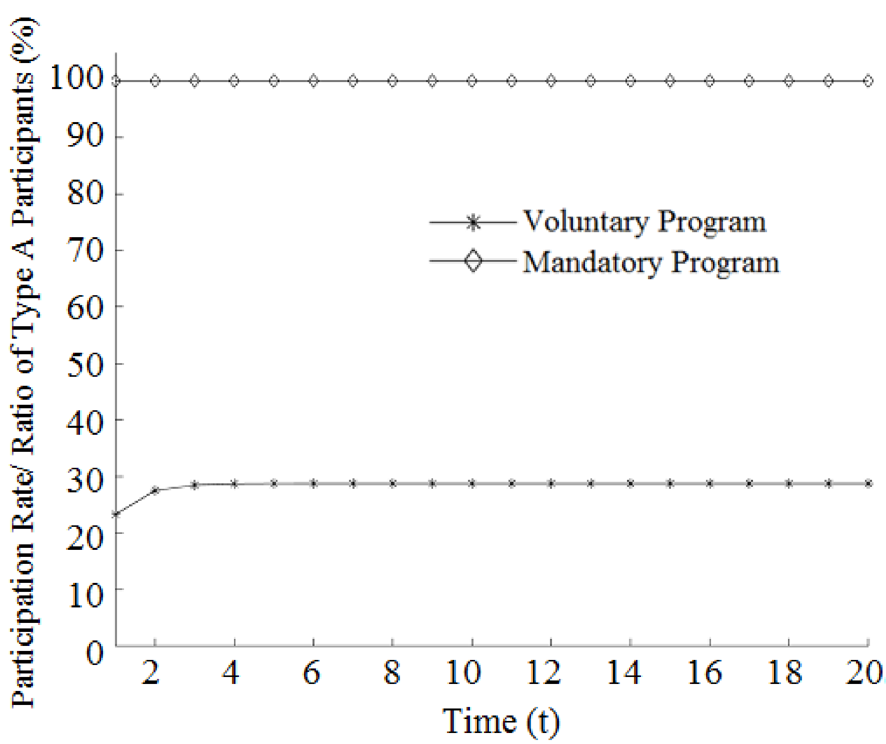

Figure 4. Participation rate and ratio of motivated Type A producers to all producers.

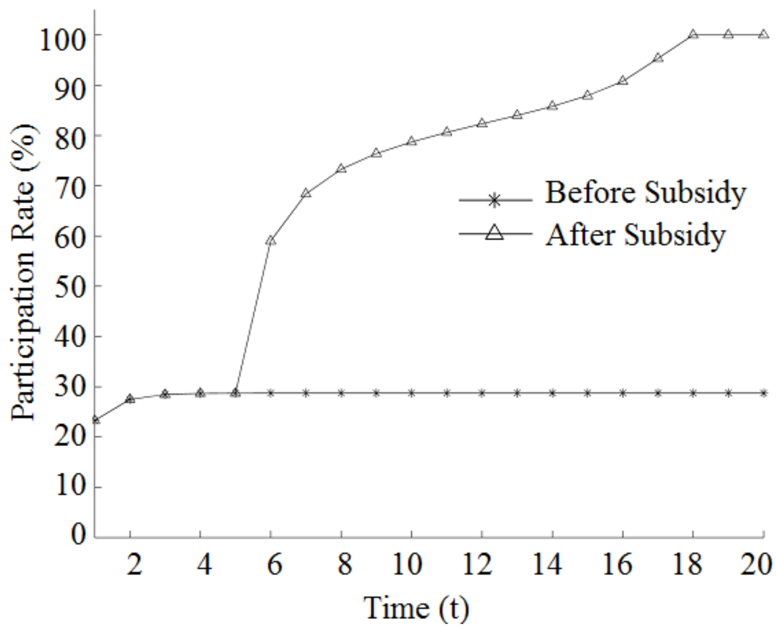

Figure 5. Subsidy and tipping—$\alpha = 0$.

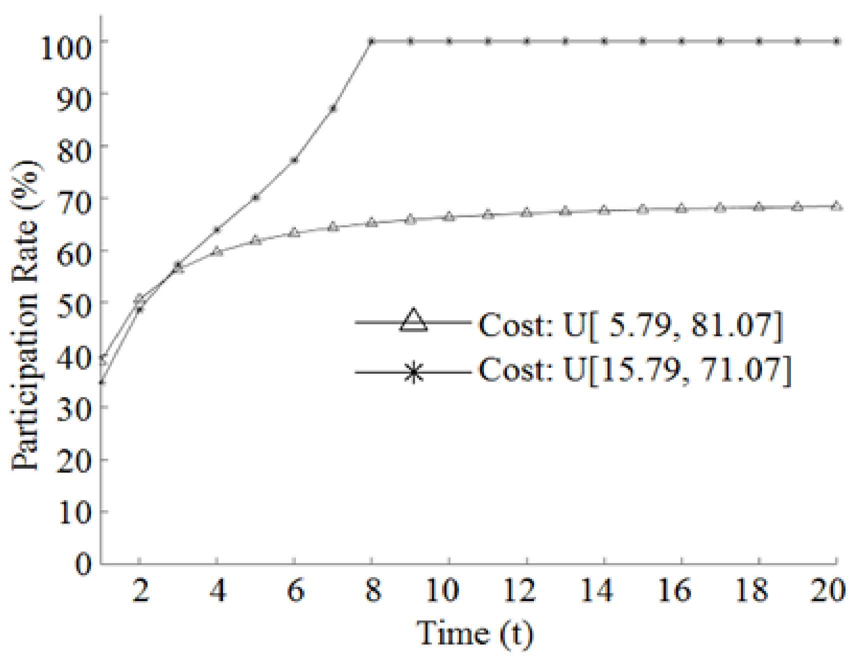

Figure 6(a). Cost heterogeneity—$\alpha = -0.5$.

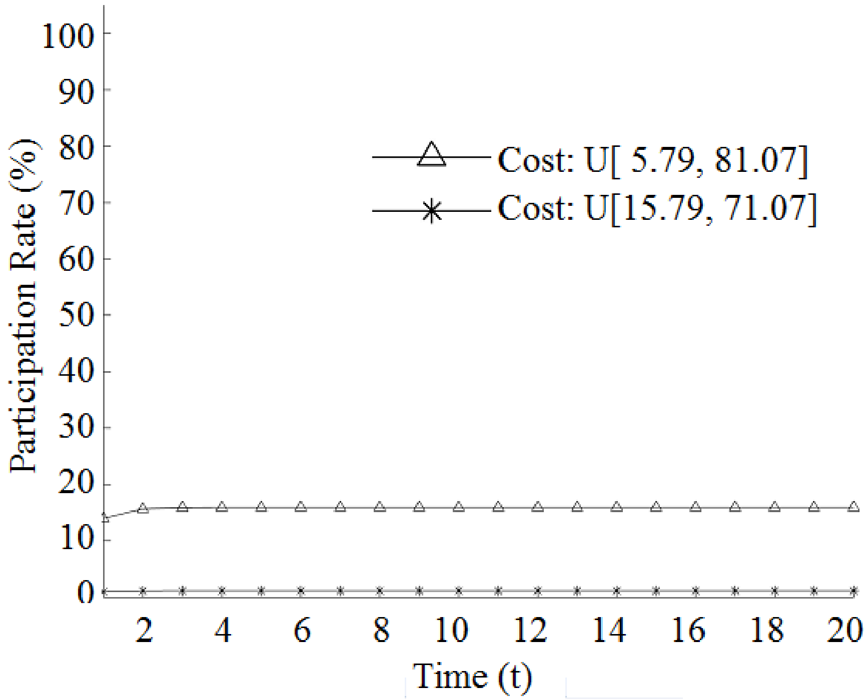

Figure 6(b). Cost heterogeneity—$\alpha = 0.3$.

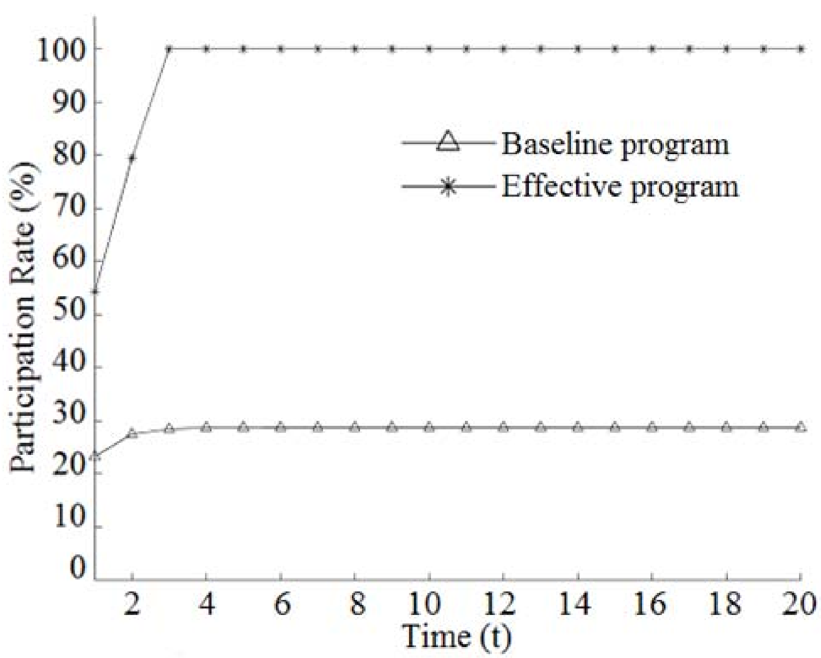

Figure 7. Effective program vs. baseline program.

Supplemental Materials

Lemma 1: The expected premium from participation will increase whenever one of the following holds: *i*) Society becomes more aware of the disease, $\partial I_t / \partial \alpha \leq 0$; *ii*) the value of an animal increases, $\partial I_t / \partial V \geq 0$, or *iii*) the average disease-free rate among silent producers decreases, $\partial I_t / \partial r_t^S \leq 0$.

Proof: The inferences follow from $\partial I_t(\cdot) / \partial \alpha = -I_t(\cdot) / (1-\alpha) \leq 0$, $\partial I_t(\cdot) / \partial V = I_t(\cdot) / V \geq 0$ and $\partial I_t(\cdot) / \partial r_t^S = (\alpha - 1)V[1 - F(r_t^S)] \leq 0$. ■

Lemma 2: Under a voluntary program, when $I_{\min} \leq \underline{c} \leq \overline{c} < I_{\max}$ then at least two equilibria exist. These are NP and FP.

Proof: If no producer participates, then $r_0^S = r^e$. The expected premium from participation is $I_{\min}$. As $I_{\min} \leq \underline{c}$, nobody participates. Therefore $(r^*, \eta^*) = (r^e, 0)$ is one equilibrium. If all producers participate, then $r = \underline{r}$. The expected premium from participation is $I_{\max}$. As $\overline{c} <$ $I_{\max}$, all producers will participate. Thus $(r^*, \eta^*) = (\underline{r}, 1)$ is another equilibrium. ■

Proposition 1: Producer participation decisions are strategic complements. That is, whenever $1 \geq \eta_t'' \geq \eta_t' \geq 0$ then $r_t^S(\eta_t') \geq r_t^S(\eta_t'')$ and $I_t(r_t^S(\eta_t'')) \geq I_t(r_t^S(\eta_t'))$.

*Proof***:** By equation (5) we have $r_t^S(\eta_t) \equiv \pi(\eta_t) r^e_{r \leq r_{t-1}^S} + (1 - \pi(\eta_t)) r^e$ where $\pi(\eta_t) =$ $\eta_t F(r_{t-1}^S) / [\eta_t F(r_{t-1}^S) + 1 - \eta_t]$ whenever $\eta_t \neq 1$. If $\eta_t = 1$, then $r_t^S(1) = \underline{r}$. Given r_{t-1}^S fixed, we can easily show that $r_t^S(\eta_t)$ is decreasing in η_t. Thus $\eta_t' \leq \eta_t''$ implies $r_t^S(\eta_t') \geq r_t^S(\eta_t'')$. By Lemma 1 it follows that $I_t(r_t^S(\eta_t'')) \geq I_t(r_t^S(\eta_t'))$. ■

Assumption 2 always holds whenever both the average disease-free rate and participation cost are uniformly distributed as $r \sim U[0,1]$ *and* $c \sim U[0,\overline{c}]$, *and also* $\gamma \equiv (1-\alpha)V \geq 2\overline{c}$.

Proof: Obviously $r^e - r^e_{r \leq r^S}$ is decreasing in r^S . Therefore, Assumption 2 will automatically hold whenever $\phi(r^S)$ is decreasing in r^S , i.e., whenever

$$\begin{aligned}
\frac{d\phi(r^S)}{dr^S} &= -\frac{d}{dr^S}\frac{1-g(r^S)}{g(r^S)F(r^S)+1-g(r^S)} \\
&= \frac{g'(r^S)}{g(r^S)F(r^S)+1-g(r^S)} + \frac{[1-g(r^S)][g(r^S)F'(r^S)+g'(r^S)F(r^S)-g'(r^S)]}{[g(r^S)F(r^S)+1-g(r^S)]^2} \\
&= \frac{g(r^S)(1-g(r^S))F'(r^S)+g'(r^S)F(r^S)}{[g(r^S)F(r^S)+1-g(r^S)]^2} \leq 0.
\end{aligned}$$

This condition is equivalent to

$$g'(r^S)F(r^S) \leq -g(r^S)(1-g(r^S))F'(r^S). \qquad \text{(SM-1)}$$

When the average disease-free rate is uniformly distributed as $r \sim U[0,1]$ and participation costs satisfy $c \sim U[0,\overline{c}]$, then $F(r^S) = r^S$, $F'(r^S) = 1$ and $I(r^S) = \gamma\int_{r^S}^1 (r - r^S)dr =$ $0.5\gamma(1-r^S)^2$.

If $I(r^S) > \overline{c}$, then $g(r^S) = 1$, $g'(r^S) = 0$ and Condition (SM-1) holds with equality. If $I(r^S) \leq \overline{c}$, then $g(r^S) = \gamma\int_{r^S}^1 (r-r^S)dr / \overline{c} = 0.5\gamma(1-r^S)^2 / \overline{c}$, and $g'(r^S) = -\gamma(1-r^S)/\overline{c} \leq 0$.

Under these specifications we can show that condition (SM-1) always holds as

$$\begin{aligned}
&-\gamma r^S(1-r^S)/\overline{c} \leq -0.5\gamma(1-r^S)^2(1-0.5\gamma(1-r^S)^2/\overline{c})/\overline{c} \\
&\Leftrightarrow 2r^S \geq (1-r^S)[1-0.5\gamma(1-r^S)^2/\overline{c}]
\end{aligned} \qquad \text{(SM-2)}$$

Assuming that $\gamma \geq 2\overline{c}$, condition (SM-2) will hold if we can show $2r^S \geq (1-r^S)[1-(1-r^S)^2]$, which immediately holds as $2 \geq (1-r^S)(2-r^S)$. ■

Proposition 2: Under Assumption 2, then over time the *i*) average disease-free rate among silent producers is non-increasing, i.e., $r_0^S \geq r_1^S \geq \cdots \geq r_k^S$; *ii*) participation premium is non-decreasing, i.e., $I_0 \leq I_1 \leq \cdots \leq I_k$; *iii*) participation rate is non-decreasing, i.e., $\eta_0 \leq \eta_1 \leq \cdots \leq \eta_k$.

Proof: The proof of part *i*) is by induction. Similar to (5) and (6), we have

$$r_1^S = \phi(r_0^S) r^e_{r \leq r_0^S} + [1 - \phi(r_0^S)] r^e = r^e - \phi(r_0^S)[r^e - r^e_{r \leq r_0^S}],$$
$$r_2^S = \phi(r_1^S) r^e_{r \leq r_1^S} + [1 - \phi(r_1^S)] r^e = r^e - \phi(r_1^S)[r^e - r^e_{r \leq r_1^S}].$$

First we know by equation (3) that $r_0^S = r^e \geq r_1^S$. We can then prove that $r_1^S \geq r_2^S$ if $\phi(r_1^S)[r^e - r^e_{r \leq r_1^S}] \geq \phi(r_0^S)[r^e - r^e_{r \leq r_0^S}]$, which immediately hold under Assumption 2.

Next, suppose that $r_{t-1}^S \geq r_t^S$ holds, we can then prove $r_t^S \geq r_{t+1}^S$. Again, similar to (5) and (6),

$$r_t^S = r^e - \phi(r_{t-1}^S)[r^e - r^e_{r \leq r_{t-1}^S}],$$
$$r_{t+1}^S = r^e - \phi(r_t^S)[r^e - r^e_{r \leq r_t^S}].$$

In order to have $r_{t+1}^S \leq r_t^S$, we need the following condition to hold:

$$\phi(r_t^S)[r^e - r^e_{r \leq r_t^S}] \geq \phi(r_{t-1}^S)[r^e - r^e_{r \leq r_{t-1}^S}]. \qquad \text{(SM-3)}$$

Again, (SM-3) holds whenever Assumption 2 is true.

Next, inference *ii*) holds by inference *i*) and Lemma 1. Based on Lemma 4 and the assumption that $\eta_0 = 0$, inference *iii*) follows immediately. ■

Lemma 4: If $\tilde{r}_t^S \leq r_t^S$, then $\tilde{I}_t > I_t$.

Proof: By Lemma 1 we have $\tilde{I}_t \equiv \tilde{I}(\tilde{r}_t^S) \geq \tilde{I}(r_t^S)$ whenever $\tilde{r}_t^S \leq r_t^S$. Under the effective program at least producers with $r \geq r_t^S$ can get the price premium. Therefore:

$$\tilde{I}_t \geq \tilde{I}(r_t^S) \geq \gamma \int_{r_t^S}^1 \left[\lambda(r) - r_t^S\right] dF(r) > \gamma \int_{r_t^S}^1 (r - r_t^S) dF(r) = I(r_t^S) \equiv I_t. \quad \blacksquare$$

Proposition 3: Compared to the baseline program, the effective program always generates a greater expected price premium whenever Assumption 2 holds. That is $\forall t \geq 1,\ \tilde{I}_t > I_t$.

Proof: As $\tilde{r}_0^S = r_0^S = r^e$, by Lemma 4 we know that $\tilde{I}_0 > I_0$, which implies that $\tilde{\eta}_1 \geq \eta_1$ under Lemma 3. Then use Proposition 1 to conclude that $\tilde{r}_1^S \leq r_1^S$.

The next step resembles the proof of Proposition 2, part *i*). Similar to (5), we have

$$r_t^S = \phi(r_{t-1}^S) r_{r \leq r_{t-1}^S}^e + [1 - \phi(r_{t-1}^S)] r^e = r^e - \phi(r_{t-1}^S)\left(r^e - r_{r_{t-1}^S}^e\right),$$

$$\tilde{r}_t^S = \phi(\tilde{r}_{t-1}^S) r_{r \leq \tilde{r}_{t-1}^S}^e + [1 - \phi(\tilde{r}_{t-1}^S)] r^e = r^e - \phi(\tilde{r}_{t-1}^S)\left(r^e - r_{\tilde{r}_{t-1}^S}^e\right).$$

Conditional on Assumption 2, we can easily see that $\tilde{r}_2^S \leq r_2^S$ as $\tilde{r}_1^S \leq r_1^S$. Similarly we know that $\forall t \geq 1,\ \tilde{r}_t^S \leq r_t^S$. By applying Lemma 4 again, we have $\forall t \geq 1,\ \tilde{I}_t > I_t$. $\blacksquare$

Sensitivity analysis in simulation.

In this section we will carry out sensitivity analyses with regard to $\underline{r}$, α and V. Other parameters fixed, we obtain the participation rates for the first 20 periods as shown in Figure SM1(a) by choosing α among $\{-1, -0.6, 0, 0.3\}$. Similarly, we choose $\underline{r} \in \{0.8, 0.82, 0.85, 0.95\}$ and the participation rate dynamics are provided in Figure SM1(b). Finally, we choose $V \in \{\$1{,}300,\ \$1{,}500, \$1{,}700, \$1{,}900\}$ and simulations are displayed in Figure SM1(c). The results in Figure SM1(a) follow from Lemma 1 and 3, where a lower α indicates a larger premium in the initial period and thus a greater participation rate during period 1. Next, by the strategic complementarity property proved in Proposition 1 we know that the equilibrium participation rate will increase as well. Similarly, Figures SM1(b) and

SM1(c) can be explained by a combination of lemmas 1 and 3.

Figure SM1(a) shows how the consequences of JD affect participation rates in a voluntary program. For example, when losses are due to decreasing productivity, we might reasonably assume that $\alpha = 0.3$. In this case the participation rate stabilizes at about 18%. However, were JD shown to have significant zoonotic effects then α would likely be negative. In cases where $\alpha \in \{-1, -0.6\}$, FP equilibrium will be reached. Figure SM1(b) indicates that the equilibrium participation rate can be influenced by producer's beliefs on within-herd disease prevalence. While our simulations have less than 10% of producers participating when the average prevalence rate is 2.5%, FP will be realized whenever average prevalence reaches 10%. Increased unit cow value will also enhance equilibrium participation, but to a very limited extent because the value range is narrow. From Figure SM1(c) we can see that, all else fixed, FP will not be attained even if the unit value is \$2,500. The effect of unit animal value on participation rate can also explain why the participation rate for beef herds is much lower than that for dairy herds (Wells, Hartmann, and Anderson 2008), although participation costs are also likely higher.

A more general comment on Figure SM1(c) is that participation rates, and so eventually disease-free rates, increase as value to be protected increases. This value could take the form of non-stock production assets such as feeding, housing and manure management investments. Such assets provide another form of complementarity beyond the present model; namely between a particular grower's asset value at risk and the participation decision rather than between grower participation decisions. But the two forms of complementarity will themselves interact in a complementary manner. That is, regions with a preponderance of competitive species X growers will have high asset values to protect and will participate. This will encourage others in the region to participate and a high region-wide participation rate is likely to promote further investment in the region's species X production sector. On the other hand, if a region has a marginal species X production sector then there will be low incentive to participate and this just confirms the region's low sector productivity.

Voluntary Program---Coarse Grading

In this section we will present our model under the alternative assumption of a coarse grading test. A coarse grading test only distinguishes two possible cases. Producers obtain a certificate when their disease-free rate is above a threshold $\hat{r}$ and no certificate otherwise. The unit livestock price of a non-participating herd is $p_t^1 = r_t^S V + (1 - r_t^S)\alpha V$, while the realized unit price of one that participates takes the following form:

$$p_t^2 = \begin{cases} r_t^S V + (1 - r_t^S)\alpha V & \text{whenever } r \le \hat{r}, \\ r_{r>\hat{r}}^e V + (1 - r_{r>\hat{r}}^e)\alpha V & \text{whenever } r > \hat{r}. \end{cases}$$

Therefore the realized premium received by a producer who participates is:

$$p_t^2 - p_t^1 = \begin{cases} 0, & \text{whenever } r \le \hat{r}; \\ \gamma(r_{r>\hat{r}}^e - r_t^S) & \text{whenever } r > \hat{r}. \end{cases}$$

The expected price premium from participating is thus:

$$I^c(r_t^S, \hat{r}) = \gamma \int_{\hat{r}}^1 (r_{r>\hat{r}}^e - r_t^S) dF(r) = \gamma (r_{r>\hat{r}}^e - r_t^S)[1 - F(\hat{r})]. \tag{SM-4}$$

Here $I^c(\cdot)$ represents the price premium function in the coarse grading case. Next, we will show that in the coarse grading system, price premium depends only on the lowest threshold. The number of thresholds and the value of other thresholds will not affect the premium. Therefore without loss of generality, we will focus on the single threshold case.

Proposition SM1: Suppose there are two coarse grading programs with $\hat{r}^1 < \hat{r}^2$. Program 1 offers the certificate whenever the tested disease-free rate satisfies $r > \hat{r}^1$. Program 2 offers a level 1 certificate whenever $r \in [\hat{r}^1, \hat{r}^2)$, and a level 2 certificate whenever $r > \hat{r}^2$. The expected premiums generated by the two programs are the same.

Proof :According to (SM-1), the expected price premium for program 1 is:

$$I^c(r_t^S, \hat{r}) = \gamma(r^e_{r>\hat{r}^1} - r_t^S)[1 - F(\hat{r}^1)] \tag{SM-5}$$

The realized price charged by a producer participating in program 2 takes the following form:

$$p_t^2 = \begin{cases} r_t^S V + (1 - r_t^S)\alpha V, & \text{whenever} \quad r \le \hat{r}^1; \\ r^e_{\hat{r}^1 < r \le \hat{r}^2} V + (1 - r^e_{\hat{r}^1 < r \le \hat{r}^2})\alpha V, & \text{whenever} \quad \hat{r}^1 < r \le \hat{r}^2; \\ r^e_{r>\hat{r}^2} V + (1 - r^e_{r>\hat{r}^2})\alpha V, & \text{whenever} \quad r > \hat{r}^2. \end{cases}$$

Since the unit livestock price from non-participating is $p_t^1 = r_t^S V + (1 - r_t^S)\alpha V$, we can calculate the realized premium from participating in program 2 as:

$$p_t^2 - p_t^1 = \begin{cases} 0, & \text{whenever} \quad r \le \hat{r}^1; \\ \gamma(r^e_{\hat{r}^1 < r \le \hat{r}^2} - r_t^S), & \text{whenever} \quad \hat{r}^1 < r \le \hat{r}^2; \\ \gamma(r^e_{r>\hat{r}^2} - r_t^S), & \text{whenever} \quad r > \hat{r}^2. \end{cases}$$

The expected price premium from participating in program 2 is:

$$\begin{aligned} I^c(r_t^S, \hat{r}^1, \hat{r}^2) &= \gamma\int_{\hat{r}^1}^{\hat{r}^2} (r^e_{\hat{r}^1 < r \le \hat{r}^2} - r_t^S) dF(r) + \gamma\int_{\hat{r}^2}^{1} (r^e_{r>\hat{r}^2} - r_t^S) dF(r) \\ &= \gamma(r^e_{\hat{r}^1 < r \le \hat{r}^2} - r_t^S)(F(\hat{r}^2) - F(\hat{r}^1)) + \gamma(r^e_{r>\hat{r}^2} - r_t^S)(1 - F(\hat{r}^2)) \\ &= \gamma r^e_{\hat{r}^1 < r \le \hat{r}^2}(F(\hat{r}^2) - F(\hat{r}^1)) + \gamma r^e_{r>\hat{r}^2}(1 - F(\hat{r}^2)) - \gamma r_t^S(1 - F(\hat{r}^1)) \\ &= \gamma r^e_{\hat{r}^1 < r \le \hat{r}^2}\text{Prob}(\hat{r}^1 < r \le \hat{r}^2) + \gamma r^e_{r>\hat{r}^2}\text{Prob}(r > \hat{r}^2) - \gamma r_t^S(1 - F(\hat{r}^1)) \\ &= \gamma r^e_{r>\hat{r}^1}\text{Prob}(r > \hat{r}^1) - \gamma r_t^S[1 - F(\hat{r}^1)] \quad \text{(By the Law of Iterated Expectations)} \\ &= \gamma r^e_{r>\hat{r}^1}[1 - F(\hat{r}^1)] - \gamma r_t^S[1 - F(\hat{r}^1)] \\ &= \gamma(r^e_{r>\hat{r}^1} - r_t^S)[1 - F(\hat{r}^1)]. \end{aligned} \tag{SM-6}$$

This is exactly the expected price premium generated by program 1, as shown in (SM-5). ■

In the coarse grading case, silent producers are comprised of two groups: participants who fail to obtain the certificate, and non-participants. Similar to the equilibrium defined in the fine grading case, we will define the equilibrium under single-threshold coarse grading as:

$$r^* = \phi(r^*) r^e_{r\le\hat{r}} + [1-\phi(r^*)] r^e;$$
$$\phi(r^*) = \frac{\eta^* F(\hat{r})}{\eta^* F(\hat{r}) + 1 - \eta^*}; \qquad \eta^* = G(I^c(r^*, \hat{r})). \tag{SM-7}$$

As a counterpart to Figure 2 in the voluntary fine grading case, Figure SM2 displays all possible types of equilibria when cost structures differ. As an example, we will show by Proposition SM2 that there are at least two possible equilibria in region R5. The proof resembles that in Lemma 2.

Proposition SM2: Under the voluntary program coarse grading case, NP and FP are two possible equilibria when $I^c(r^e, \hat{r}) \le \underline{c} \le \overline{c} \le I^c(r^e_{r\le\hat{r}}, \hat{r})$.

We seek now to prove Proposition SM3, a counterpart to Proposition 2 in the fine grading case. In order to do so we will first show in Lemma SM1 that a counterpart of Assumption 2 always holds in the coarse grading case.

Lemma SM1: In the coarse grading case, an equivalent to Assumption 2 of the fine grading case will always hold. That is $J(r_t^S, \hat{r}) = \phi(r_t^S, \hat{r})(r^e - r^e_{r\le\hat{r}})$ is decreasing in $r_t^S \in [\underline{r}, r^e]$ where $\phi(r_t^S, \hat{r}) = G(I^c(r_t^S, \hat{r}))F(\hat{r}) / \left[G(I^c(r_t^S, \hat{r}))F(\hat{r}) + 1 - G(I^c(r_t^S, \hat{r}))\right]$.

Proof: As $r^e - r^e_{r\le\hat{r}}$ is a constant, we only need $\phi(r_t^S, \hat{r})$ to be decreasing in $r_t^S \in [\underline{r}, r^e]$. This is obvious as $G(I^c(r_t^S, \hat{r}))$ is decreasing in r_t^S and $F(\hat{r})$ is fixed. ■

Proposition SM3: In coarse grading case, the following three inferences always apply: *i*) average disease-free rate among silent producers will be non-increasing, i.e., $r_0^S \ge r_1^S \ge \cdots \ge r_k^S$; *ii*) participation premium will be non-decreasing, i.e., $I_0 \le I_1 \le \cdots \le I_k$ ($I_k \equiv I^c(r_k^S)$); *iii*) participation rate will be non-decreasing, i.e., $\eta_0 \le \eta_1 \le \cdots \le \eta_k$.

Proof: The proof follows directly from Proposition 2 and Lemma SM1. ■

Lastly we will briefly revisit Example 1 in the coarse grading case, where an additional threshold parameter takes value $\hat{r} = 0.98$. It follows that:

$$I^c(r^e_{r\le\hat{r}}, \hat{r}) = \gamma\int_{\hat{r}}^{1}[r^e_{r>0.98} - r^e_{r\le 0.98}]dF(r) = 0.8\times 500\int_{0.98}^{1}\frac{[r^e_{r>0.98} - r^e_{r\le 0.98}]}{1-0.90}dr = 4.$$

Therefore $\overline{c} \ge \underline{c} \ge I^c(r^e_{r\le\hat{r}}, \hat{r})$. Now the case of Example 1 is located in region R3 of Figure SM2, where the only equilibrium is NP and tipping will not occur. Therefore strategic complementarity as provided in Proposition SM3, may not lead to tipping. Next we will show that in a more general setup, coarse grading generates a smaller expected price premium, i.e., less incentive for producers to participate.

Proposition SM4: Assume that $\hat{r} > r^e$. Then price premium under the coarse grading system $I^c(r^S_t, \hat{r})$ is no greater than that under the fine grading system, $I(r^S_t)$ for any given $r^S_t \in [0,1]$.

Proof: Calculate

$$\begin{aligned} I^c(r^S_t, \hat{r}) &= \gamma\int_{\hat{r}}^{1}(r^e_{r\ge\hat{r}} - r^S_t)dF(r) = \gamma\int_{\hat{r}}^{1}(r - r^S_t)dF(r) \\ &< \gamma\int_{r^S}^{1}(r - r^S_t)dF(r) \quad (\text{By } r^S_t \le r^e < \hat{r}) \\ &= I(r^S_t). \quad \blacksquare \end{aligned}$$

Note that condition $\hat{r} > r^e$, which means that participants only obtain a certificate when their disease-free rate is above the average, is a sufficient condition for Proposition SM4 to hold. This is because $r^S_t \le r^S_0 = r^e$ (by eqn. (5)), so producers with disease-free rate $r \in (r^S_t, \hat{r}]$ will obtain a premium in the fine grading case, but not in a coarse grading case. Thus ex-ante a producer has a lower expected premium in the coarse grading system.

Mandate---Coarse Grading

The average disease-free rate among silent producers, who are comprised solely of the producers that obtain no certificate, is $r^e_{r\le\hat{r}} = E(r \mid r \le \hat{r})$. Thus by (SM-4) the expected price premium from participation is:

$$I^c(r^e_{r\le\hat{r}}, \hat{r}) = \gamma[1 - F(\hat{r})][r^e_{r>\hat{r}} - r^e_{r\le\hat{r}}]. \qquad \text{(SM-8)}$$

Similar to Figure 3, Figure SM3 also displays three possible cases. These are:

1. $\underline{c} \le I^c(r^e_{r\le\hat{r}}, \hat{r}) \le \overline{c}$. This cost structure is represented by region M1, where both types of participants exist. Those participants with $c \in [\underline{c}, I^c(r^e_{r\le\hat{r}}, \hat{r}))$ are motivated type A participants, and those with $c \in (I^c(r^e_{r\le\hat{r}}, \hat{r}), \overline{c}]$ are type B participants;
2. $\underline{c} \ge I^c(r^e_{r\le\hat{r}}, \hat{r})$. This is represented by M2, where the market is solely comprised of unmotivated type B participants;
3. $\overline{c} \le I^c(r^e_{r\le\hat{r}}, \hat{r})$. This is represented by M3, where the market is solely comprised of motivated type A participants.

As $\underline{c} = 5.5 \ge I^c(r^e_{r\le\hat{r}}, \hat{r}) = 4$, we know that the case in Example 1 is now located in M2. This means that the market is comprised solely of type B participants, who would choose not to participate if the government spends no effort on auditing. As $I^c(r^e_{r\le\hat{r}}, \hat{r}) \le I_{\max}$,[6] region M3 of Figure 4 is larger than M3 of Figure SM3. Therefore, *ceteris paribus*, the coarse grading incentive structure entails no less implementation cost than the fine grading structure.

[6] This follows as a combination of results in Proposition SM4 and Lemma 1. The former implies that $I^c(r^e_{r\le\hat{r}}, \hat{r}) \le I(r^e_{r\le\hat{r}})$, while from the latter we know that $I(r^e_{r\le\hat{r}}) \le I_{\max}$.

For the purposes of simulation we assume that the average disease-free rate is uniformly distributed as $r \sim U[\underline{r},1]$ and participation cost is uniformly distributed as $c \sim U[\underline{c},\overline{c}]$.

Voluntary program: Coarse grading

By (SM-4), the expected price premium from participating in the program in period t is:

$$I^c(r_t^S,\hat{r}) = \gamma\int_{\hat{r}}^{1}\frac{(r_{r\geq\hat{r}}^e - r_t^S)}{1-\underline{r}}dr \ = \gamma(0.5(1+\hat{r}) - r_t^S)\frac{1-\hat{r}}{1-\underline{r}}. \qquad \text{(SM-9)}$$

Similar to (11), the disease-free rate among silent sellers in period $t+1$ is:

$$\begin{aligned}
&r_{t+1}^S = \phi(r_t^S,\hat{r})r_{r\leq\hat{r}}^e + [1-\phi(r_t^S,\hat{r})]r^e; \\
&\phi(r_t^S,\hat{r}) = \frac{G(I^c(r_t^S,\hat{r}))F(\hat{r})}{G(I^c(r_t^S,\hat{r}))F(\hat{r}) + 1 - G(I^c(r_t^S,\hat{r}))}; \\
&G(I^c(r_t^S,\hat{r})) = \frac{I^c(r_t^S,\hat{r}) - \underline{c}}{\overline{c} - \underline{c}}; \qquad F(\hat{r}) = \frac{\hat{r} - \underline{r}}{1-\underline{r}}; \\
&r_{r\leq\hat{r}}^e = \frac{\hat{r} + \underline{r}}{2}; \qquad r^e = \frac{1+\underline{r}}{2}.
\end{aligned} \qquad \text{(SM-10)}$$

From initial values $r_0^S = r^e$ and $\hat{r}$, we can calculate the premium $I_0 = I(r_0^S,\hat{r})$ by (SM-9). Then given r_0^S and I_0, we can solve for r_1^S by (SM-10) and I_t and r_{t+1}^S can be solved for $t \geq 1$ while participation rate $G(I^c(r_t^S,\hat{r}))$ in each period can also be obtained.

Mandate: Coarse grading

The expected price premium from participating in the program is:

$$\begin{aligned}
I^c(r_{r\leq\hat{r}}^e,\hat{r}) &= \gamma\int_{\hat{r}}^{1}\frac{r_{r>\hat{r}}^e - r_{r\leq\hat{r}}^e}{1-\underline{r}}dr = \gamma\frac{(r_{r>\hat{r}}^e - r_{r\leq\hat{r}}^e)(1-\hat{r})}{1-\underline{r}} \\
&= \gamma\frac{[0.5(1+\hat{r}) - 0.5(\hat{r}+\underline{r})](1-\hat{r})}{1-\underline{r}} = 0.5\gamma(1-\hat{r}).
\end{aligned} \qquad \text{(SM-11)}$$

Thus among market participants the proportion with the incentive to participate is:

$$G(0.5\gamma(1-\hat{r})) = \frac{0.5\gamma(1-\hat{r}) - \underline{c}}{\overline{c} - \underline{c}}. \tag{SM-12}$$

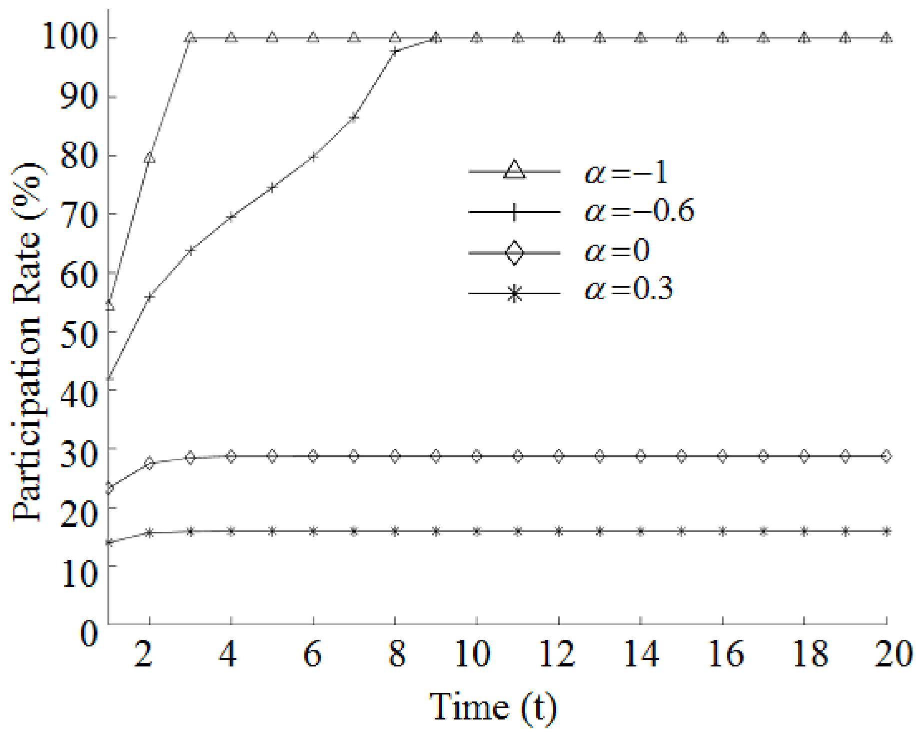

Figure SM1(a). Participation rates under different values of α .

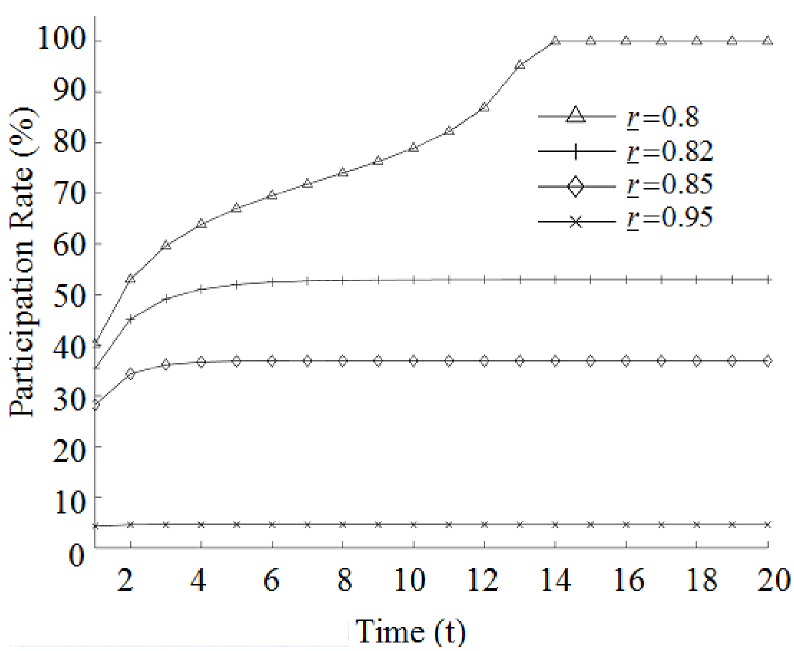

Figure SM1(b). Participation rates under different values of $\underline{r}$.

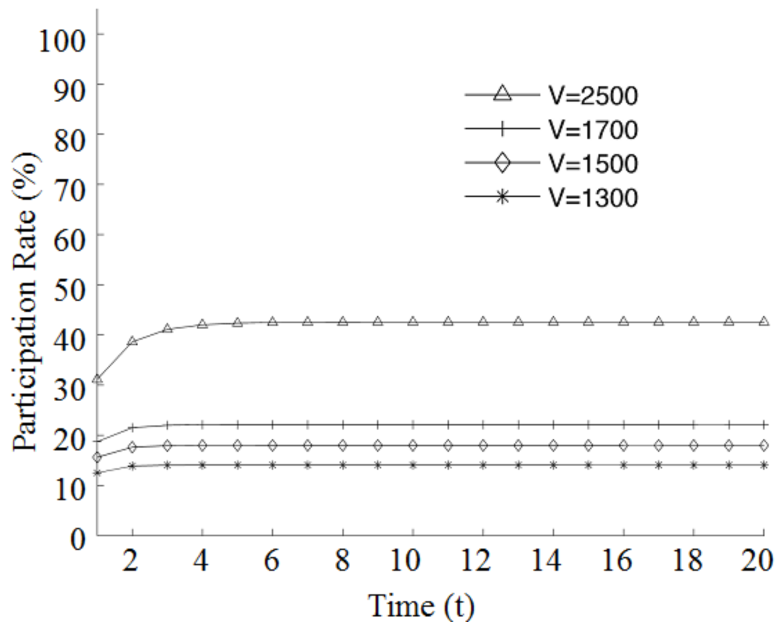

Figure SM1(c). Participation rates under different values of V .

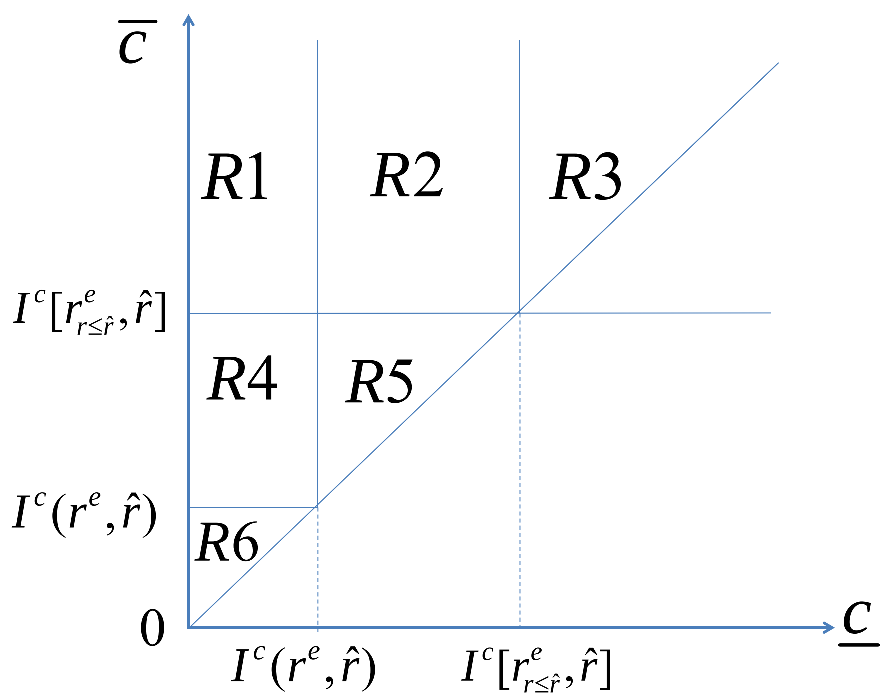

Figure SM2. Equilibria under different cost structures—Voluntary program, coarse grading.

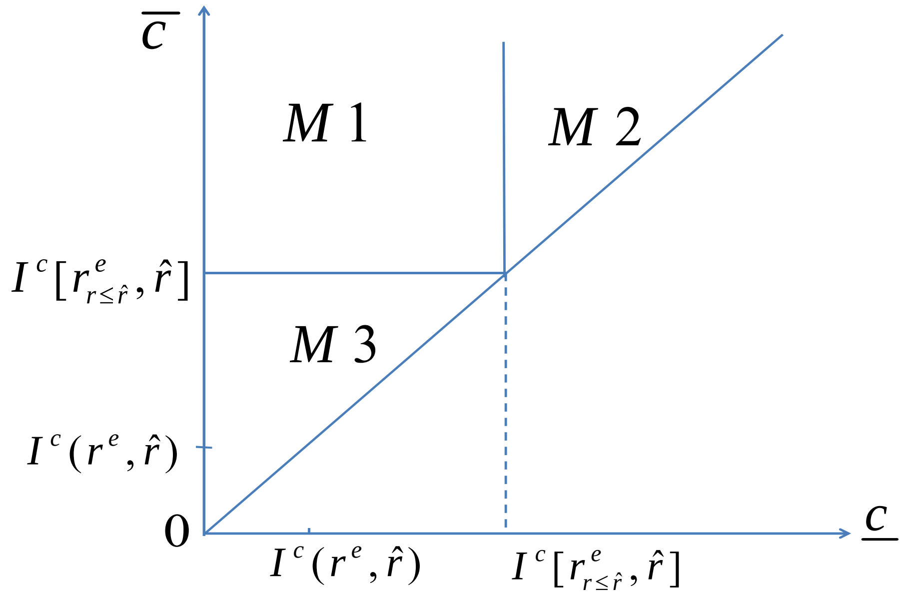

Figure SM3. Participant types under different costs—Mandatory program, coarse grading.