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Bankruptcy Risk and the Performance of Market-based Pollution Control Policies

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BANKRUPTCY RISK AND THE PERFORMANCE OF MARKET-BASED POLLUTION CONTROL POLICIES

A Thesis Presented

by

Wei Zhang

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DEDICATION

To the time lost.

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ABSTRACT

BANKRUPTCY RISK AND THE PERFORMANCE OF MARKET-BASED POLLUTION CONTROL POLICIES

SEPTEMBER 2008

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We study the impacts of bankruptcy risk on the performance of market-based pollution control policies. In Chapter one, we concentrate on emissions trading markets. We find that firms that risk bankruptcy demand more permits than if they were financially secure. Thus, bankruptcy risk in a competitive market for tradable permits causes an inefficient distribution of these permits among firms. Moreover, the equilibrium distribution of permits is dependent on the initial allocation of permits. Thus, the main reasons for implementing emissions trading markets do not hold when some firms are financially insecure. In fact, the inefficiency that is associated with bankruptcy risk is worsened if financially insecure firms are given a smaller share of the initial allocation of permits.

In chapter two, we investigate the influences of bankruptcy risk on imperfectly enforced emissions taxes. Under favorable, but not unrealistic conditions, an imperfectly enforced emissions tax produces an efficient allocation of individual emissions control; the aggregate level of control is the same whether enforcement of a tax is sufficient to induce the full compliance of firms or not, and differences in individual violations are independent of firm-level differences. All of these desirable characteristics disappear when some firms under an emissions tax risk bankruptcy—the allocation of emissions control is inefficient, imperfect enforcement causes higher aggregate emissions, and financially insecure firms choose higher violations.

CONTENTS

Page

CHAPTER 1

BANKRUPTCY RISK AND EMISSIONS TRADING MARKETS

1.1 Introduction

The fundamental value of competitive emissions trading markets, as well as other regulatory attempts to restrict behavior by allocating tradable property rights, is that they are predicted to produce distributions of individual emissions control decisions that minimize the aggregate abatement costs of reaching a predetermined environmental quality target. Moreover, the equilibrium distribution of emissions control is independent of the initial allocation of emissions permits, giving regulators the freedom to use the initial allocation of permits to pursue other objectives, such as those arising from equity concerns or the exercise of political power, without upsetting the efficiency property of emissions trading (Montgomery 1972).

Of course, the performance of emissions trading schemes depends critically on the assumption of competitive permit trading. Hahn (1984) was the first to demonstrate that market power in an emissions trading scheme would generally lead to an inefficient distribution of emissions control responsibilities. Under the assumption that all firms expect one are price takers, the total expenditure on abatement would exceed the cost-minimizing solution unless the firm with market power could receive an amount of permits equal to the number that it chooses to hold in equilibrium. If inefficiency is measured by the extent to which abatement costs exceed the minimum required to achieve a fixed target, it rises as the initial allocation of permits to the firm with market power increases above or decreases below the equilibrium amount it holds. That is, the initial allocation of permits matters, with regard not only to equity considerations but also to cost.[1]

Stavins (1995) examined the impact of transaction costs on tradable permit systems. Assuming that transaction costs are a function of the size of trades, it is shown that in the presence of transaction costs total expenditure on pollution control, even excluding transaction costs would exceed the cost-minimizing solution if the initial allocation deviates from what would be the equilibrium distribution in the absence of transaction costs. If marginal transaction costs are constant, the initial allocation of permits has no effect on the equilibrium distribution of control responsibilities and aggregate abatement costs. However, the presence of variable marginal transaction costs would make the equilibrium distribution of control levels depend on the initial allocation of permits. Thus, in the presence of transaction costs the initial distribution of permits can matter in terms of efficiency, not only in terms of equity.[2]

The motivation of this chapter is to build the connection between firms' financial status and emissions trading markets via the limited liability effect. As market power and transaction costs, we suspect that bankruptcy risk is another source of allocation inefficiency. With the continuing application of cap-and-trade into new settings, it is virtually certain that regulators will confront, or have already confronted,

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[1] The literature on market power in emissions trading programs is quite extensive. See Tietenberg (2006) for a thorough review of this literature.

[2] A number of authors have considered how transaction costs have affected the performance of actual trading programs. Cason and Gangadharan (2003) provide an excellent review of this literature. The primary motivation of their paper is to use laboratory markets to test the impacts of transaction costs on transferable permit markets. Their results generally support the conclusions of Stavins (1995).

situations involving financially distressed polluters. Thus, knowledge of how the financial health of regulated firms can impact the performance of emissions trading schemes is an important consideration in the design and evaluation of these policies.

We are certainly not the first to demonstrate that the financial health of firms can impact the performance of markets. Brander and Lewis (1986) first examined the connection between firms' financial structure and output market via the limited liability effect—firms controlled by shareholders have an incentive to pursue output strategies that raise returns in good states and lower returns in bad states. A Cournot duopolists model was used in their work, in which the financial structure of the two firms are first decided and then output levels are selected taking their financial composition as given. Assuming random profits and symmetry between the two firms, the equilibrium output of a firm rises with its own debt level and associated bankruptcy risk, but decreases with its rival's debt level.

We are also not the first to demonstrate that bankruptcy risk may impact regulatory designs, including environmental and natural resource policies. Spiegel and Spulber (1994) investigate the interactions between the investment and financial decisions of regulated firms and the pricing choices of regulators. The regulatory process was modeled as a three-stage game in which a regulated firm chooses capital structure first, then the market value of the firm's debt and equity are established in a competitive capital market and finally the regulator sets the firm's price. They found that in equilibrium the regulated firm issues a positive amount of debt and hence its risk of bankruptcy is positive. The optimal regulated price increases in the firm's debt obligation and decreases in the firm's investment level.

Damania (2000) explores the link between pollution taxes and the financial and output decisions of firms in an oligopolistic industry facing demand uncertainty. Following a model analogous to Brander and Lewis (1986), it is shown that pollution taxes may induce firms to alter their financial structure, which in turn influences both output market and effectiveness of pollution taxes. Since an emissions tax on a leveraged firm will not only increase production costs, but also affects the firm's ability to meet its debt obligations, there are circumstances under which highly leveraged firms may respond to pollution taxes by actually increasing their output. In a more recent work, Damania and Bulte (2006) relate the harvest decisions of firms in a fishery to the financial structure of the industry and regulatory control. Contrary to predictions about the decision of firms in the absence of bankruptcy risk, they demonstrate that the risk of bankruptcy may cause firms to increase their harvests and violations of harvest quotas if noncompliance penalties are increased or harvest quotas are reduced.

To our knowledge our work is the first to examine how the risk of bankruptcy affects the performance of tradable property rights regulations. We demonstrate that firms under an emissions trading scheme that face a positive risk of bankruptcy will demand more emissions permits than they would if they did not risk bankruptcy. Consequently, a significant number of financially distressed firms will cause the equilibrium distribution of emission control responsibilities to differ from the distribution that minimizes aggregate abatement costs. Moreover, the equilibrium distribution of control and the loss induced by financially distressed firms will depend on the initial distribution of permits—a larger initial allocation of emissions permits to distressed firms will reduce their risk of bankruptcy. Thus, there are welfare consequences of the initial distribution of permits that are not present when emissions markets do not include financially distressed firms. In fact, distributing a greater number of permits to distressed firms reduces the excess aggregate costs of emissions control that is due to bankruptcy risk.

The rest of this chapter is organized as follows: In the next section we lay out a simple model of a value-maximizing firm that may risk insolvency. In section 3 we investigate the effect of financial distress on a firm's demand for emissions permits and demonstrate that bankruptcy risk upsets the efficiency property that is associated with competitive emissions trading. In section 4 we demonstrate how bankruptcy risk affects emissions markets, particularly the efficiency consequences of the initial distribution of emissions permits. We conclude in section 5 with a discussion of the policy implications of this work.

1.2 A Model of a Value-maximizing Firm under Emissions Trading

In this section we present a model of a firm seeking to maximize its expected value while operating under an emissions trading scheme. Given optimal output and input choices, the firm's profit is $\pi(e)(1+z)$ excluding permit payments. e is the firm's emissions and z is a continuous random variable that is independently (but not necessarily identically) distributed in the population of regulated firms. This random variable reflects the effects of uncertainty on the firm's profit, such as the effects of random shifts in the demand for the firm's output or random changes in factor prices. The probability density function of z is $g(z)$ with support $[\underline{z}, \overline{z}]$. The expectation of z is zero so the firm's expected profit is simply $\pi(e)$. The value of z is realized after all production and permit market decisions have been made.

We assume that the firm's expected profit, $\pi(e)$, is strictly concave in the firm's emissions. In the absence of inducement to control its emissions, the firm's emissions are determined by $\pi'(e) = 0$, the solution to which is denoted e^m. It will become obvious in the next section (particularly footnote 3) that the way we have modeled the uncertainty the firm faces implies that it chooses e^m when it is not regulated whether it risks bankruptcy or not. The implementation of an emissions trading scheme generates a price for emissions that motivates the firm to reduce its emissions below e^m. As is standard, we define the firm's abatement costs as the difference between its expected profit when it does not control emissions and its expected profit when it reduces emissions. That is, for $e \in [0, e^m]$, the firm's abatement costs are $c(e) = \pi(e^m) - \pi(e)$. Moreover, the firm's marginal abatement cost function is $-c'(e) = \pi'(e)$. We assume that $\pi(e) > 0$ for $e \in [0, e^m]$; that is, the firm's expected profit is strictly greater than zero in the relevant range of emissions.

The firm receives an initial endowment of permits l. Each permit gives the firm the right to release one unit of emissions. Assume that the enforcement of the emissions trading program is sufficient to induce full compliance, so that the firm holds the same number of emissions permits as its emissions. The market for emissions permits is perfectly competitive so that trade establishes a constant price per permit p. The firm's expenditure or revenue from permit transactions is $p(e-l)$.

Here, we focus on one compliance period in which the firm's financial structure is fixed and fully captured by its equity A and its debt obligation D. Given a realization of z, the value of the firm is

$$v(e,z)=\pi(e)(1+z)-p(e-l)-D+A. \qquad [1.1]$$

If $v(e,z)$ turns out to be negative, the firm's losses exceed its equity. It then declares bankruptcy and uses its equity to partially pay off its creditors. Apart from losing its equity, there are no other costs of declaring bankruptcy. If $v(e,z)$ turns out to be greater than zero, the firm remains solvent. Note that the firm is willing to tolerate an operating loss if the loss does not exceed its equity.

Define a critical breakeven state, $\hat{z}$, in which the firm's equity is just sufficient for the firm to avoid bankruptcy:

$$\hat{z}=z \mid v(e,\hat{z})=\pi(e)(1+\hat{z})-p(e-l)-D+A=0. \qquad [1.2]$$

Solving for $\hat{z}$ yields

$$\hat{z}=\frac{p(e-l)+D-A}{\pi(e)}-1. \qquad [1.3]$$

If the realized value of z is greater than $\hat{z}$, the firm remains solvent; but it is insolvent if the realized value of z is less than $\hat{z}$. The probability that the firm avoids bankruptcy is the probability that $z \geq \hat{z}$; that is, $\int_{\hat{z}}^{\overline{z}} g(z)dz$. Clearly, the probability of bankruptcy increases with $\hat{z}$. Note that if $\hat{z} \leq \underline{z}$, the firm is financial secure in the sense that it does not risk bankruptcy. At the other end of the range of z, if $\hat{z} \geq \overline{z}$, the firm will definitely be insolvent. Obviously, in this case the firm will not even bother to begin production. However, in the more interesting cases in which $\hat{z} \in (\underline{z}, \overline{z})$, the probabilities that the firm will be solvent or insolvent are both strictly positive.

From [1.3], note that the first derivatives of $\hat{z}$ are:

$$\hat{z}_A = \frac{-1}{\pi(e)} < 0, \quad \hat{z}_l = \frac{-p}{\pi(e)} < 0, \quad \hat{z}_D = \frac{1}{\pi(e)} > 0,$$

$$\hat{z}_p = \frac{(e-l)}{\pi(e)}, \text{ and } \hat{z}_e = \frac{p - \pi'(e)(1+\hat{z})}{\pi(e)}. \qquad [1.4]$$

(Throughout, derivatives are indicated by subscripts in the usual fashion). Recalling that $\pi(e)$ is greater than zero. For $\hat{z} \in (\underline{z}, \overline{z})$, an increase in the firm's equity reduces the breakeven value of z and the probability that it will be forced to declare bankruptcy. Similarly, since the initial allocation of permits is just another asset, an increase in the firm's initial allocation of permits reduces $\hat{z}$ and the probability that it will be insolvent. Of course, an increase in the firm's debt payment, D, increases $\hat{z}$ and the probability the firm will be insolvent. The effect of a change in the price of permits on the probability of insolvency depends on whether the firm is a net buyer or net seller of permits. If the firm sells permits, an increase in the price of permits increases the value of the firm and reduces its bankruptcy risk. If the firm buys permits, a price increase raises the likelihood that the firm will be insolvent. Finally, the effect of the firm's level of emissions on the likelihood of insolvency depends on the relationship between the permit price and the firm's marginal profit evaluated at $\hat{z}$. In general, the sign of $\hat{z}_e$ is indeterminate, but it is easy to show that it is positive when the firm chooses its emissions optimally.

The manager of the firm is risk neutral and chooses the firm's emissions to maximize the expected value of the firm. Denote the expectation of $v(e,z)$ as $V(e,z)$[3]. Therefore,

$$V(e,z)=\int_{\underline{z}}^{\hat{z}}(-A)g(z)dz+\int_{\hat{z}}^{\overline{z}}\left[\pi(e)(1+z)-p(e-l)-D\right]g(z)dz\,. \quad [1.5]$$

Throughout we assume that $V(e,z)$ is strictly concave in its emissions for every feasible value of z, and that the firm optimally chooses a positive level of emissions. Note that the firm only considers states of insolvency because it risks losing its equity. The limited liability has important consequences for the firm's optimal choice of emissions. We will investigate this in the next section.

1.3 Bankruptcy Risk and a Firm's Demand for Emissions Permits

In the standard demonstration of the ability of a competitive emissions market to distribute individual emissions efficiently, firms maximize profit without fearing the possibility of bankruptcy. In our model, if a firm is financially secure, $\hat{z}\le\underline{z}$ and [1.5] reduces to $\pi(e)-p(e-l)-D$. Clearly, the firm takes its equity into account when making decisions only when it risks losing it. When there is no such risk, the firm chooses its emissions so that $p=\pi'(e)$, which is the familiar condition that a firm chooses its permit demand and emissions to equate its marginal abatement cost to the going permit price. (Recall that $\pi'(e)=-c'(e)$). If no firm under an emissions trading program faces bankruptcy, their emissions choices equate their marginal abatement costs, which forms the set of necessary conditions for minimizing

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[3] We could model the expected value of the firm in another way, $V(e,z)=\int_{\underline{z}}^{\hat{z}}0g(z)dz+\int_{\hat{z}}^{\overline{z}}[\pi(e)(1+z)-p(e-l)-D+A]g(z)dz$. There is no material difference between the two forms. [1.5] represents the flow of shareholder's benefits, but this one stands for the stock of it.

the aggregate abatement costs of holding aggregate emissions to some exogenous level. Moreover, it is obvious that the firm's choice of emissions does not depend on the initial permit allocations.

Matters are very different if some firms under an emissions trading program risk bankruptcy. Given our assumptions that [1.5] is strictly concave in the firm's emissions and that the firm chooses positive emissions, the following first order condition is both necessary and sufficient to uniquely determine its optimal choice of emissions: $V_e = \int_{\hat{z}}^{\bar{z}} [\pi'(e)(1+z) - p] g(z) dz - \hat{z}_e g(\hat{z}) [\pi(e)(1+\hat{z}) - p(e-l) - D + A] = 0$. Using the definition of $\hat{z}$ provided by [1.2], the first order condition simplifies to

$$V_e = \int_{\hat{z}}^{\bar{z}} [\pi'(e)(1+z) - p] g(z) dz = 0 . \qquad [1.6]$$

Rearranging this equation gives us

$$p = \pi'(e)[1 + E(z \mid z > \hat{z})] , \qquad [1.7]$$

where

$$E(z \mid z > \hat{z}) = \int_{\hat{z}}^{\bar{z}} z g(z) dz \Big/ \int_{z}^{\bar{z}} g(z) dz \qquad [1.8]$$

is the expectation of z (E is the expectation operator) when its distribution is truncated on the left at $\hat{z}$.[4] Therefore, $E(z \mid z > \hat{z})$ is the expectation of z conditional on the firm being solvent.[5] See Appendix for proof. In fact, the right hand side of [1.7] is the firm's expected marginal profit over states in which it avoids bankruptcy. Why does the firm ignore states in which it is bankrupt when choosing

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[4] A financially distressed firm's choice of emissions in an unregulated setting is determined from [1.7] by setting $p = 0$. Doing so yields e^m, the solution to $\pi'(e) = 0$. This is the same unregulated level of emissions that the firm would choose if it did not risk bankruptcy.

[5] One should be careful to not interpret $p = \pi'(e)[1 + E(z \mid z > \hat{z})]$ as the inverse permit demand function for a financially distressed firm, because the permit price p appears in $E(z \mid z > \hat{z})$.

emissions? It is because its loss in bankrupt states is its constant level of equity, A, which does not depend on its choice of emissions. The fixed limit on the firm's bankruptcy liability causes it to choose its emissions to optimize over only the states in which it will be solvent. This is analogous to the limited liability effect Brander and Lewis (1986) referred to.

The presence of $E(z \mid z > \hat{z})$ in [1.7] is an adjustment to the firm's choice of emissions that reflects its risk of bankruptcy. When $\hat{z} \leq \underline{z}$, the probability of bankruptcy is zero, [1.8] reduces to $E(z) = 0$ because the distribution of z is no longer truncated, and [1.7] reduces to $p = \pi'(e)$. Moreover, since $\int_{\hat{z}}^{\overline{z}} zg(z)dz > \int_{\underline{z}}^{\overline{z}} zg(z)dz = 0$ as $\hat{z} \in (\underline{z}, \overline{z})$, $E(z \mid z > \hat{z})$ is strictly positive when the firm risks bankruptcy. This implies that a financially distressed firm will choose its emissions so that $p > \pi'(e)$, which implies further that, given the permit price, its emissions will be higher than if it did not risk bankruptcy.

The fact that a financially insecure firm does not equate its marginal abatement costs to the going price of permits leads directly to one of our main results about the impact of financial insecurity on the performance of competitive emissions trading. That is, an emissions trading program that contains financially insecure firms will fail to distribute emissions control in the way that minimizes aggregate abatement costs. Accomplishing this objective requires that all firms' emissions choices equate their individual marginal abatement costs. However, firms that risk bankruptcy choose levels of emissions so that their marginal abatement costs are lower than the going permit price, while those firms that do not risk bankruptcy choose their emissions to equate their marginal abatement costs to the permit price. Moreover, the marginal abatement costs among financially distressed firms will differ, because the values of $\hat{z}$ will likely vary across these firms and the densities $g(z)$ may vary as well. Since the permit market will not equate the firms' marginal abatement costs, aggregate abatement costs will not be minimized. Thus, the main reason for implementing emissions trading programs does not hold in situations involving firms that risk bankruptcy.

Moreover, the distribution of emissions control will not be independent of the initial allocation of permits, because financially distressed firms' demands for permits will depend on their permit allocations. To see why, obtain the comparative static, $\partial e / \partial l = -V_{el} / V_{ee}$, in the usual manner. Since $V_{ee} < 0$ by assumption, the sign of $\partial e / \partial l$ is the same as the sign of V_{el}. Differentiate [1.6] with respect to l and substitute $\hat{z}_l$ from [1.4] into the result to obtain $V_{el} = \left(p/\pi(e)\right)\left(\pi'(e)(1+\hat{z})-p\right)g(\hat{z})$. To sign this, first note that 搽 $E(z \mid z > z)$; that is, $\hat{z}$ is less than the expectation of z when its distribution is truncated at $\hat{z}$. Furthermore, since $\pi'(e)[1+E(z \mid z > \hat{z})] \; - p = 0$ from [1.6], 搽 $E(z \mid z > z)$ implies $\pi'(e)(1+\hat{z}) - p < 0$. Therefore, $V_{el} < 0$ and $\partial e / \partial l < 0$, which reveals that a financially distressed firm's emissions are decreasing in its initial allocation of permits. Intuitively, an increase in a firm's initial allocation of permits increases the value of the firm, all else equal. Since this then reduces the risk of bankruptcy of a financially distressed firm, it will choose its emissions so that the gap between the permit price and $\pi'(e)$ is reduced. In turn this implies lower emissions for a given permit price. Thus, a higher allocation of permits to a financially distressed firm reduces its bankruptcy risk and causes it to choose lower emissions.

To complete this section, let us determine the effect of changes in permit price on a financially distressed firm's optimal emissions. As above, the comparative static $\partial e/\partial p = -V_{ep}/V_{ee}$ has the same sign as V_{ep}. From [1.6] and $\hat{z}_p$ from [1.4] obtain $V_{ep} = -\int_{\hat{z}}^{\bar{z}} g(z)dz - \frac{e-l}{\pi(e)}[\pi'(e)(1+\hat{z})-p]g(\hat{z})$.

Note that the first term of V_{ep} is negative. However, recall from above that $\pi'(e)(1+\hat{z})-p<0$ so the sign of the second term of V_{ep} depends on whether the firm is a net buyer or seller of permits. If the firm sells permits $(e<l)$, V_{ep} and $\partial e/\partial p$ are negative. Thus, if a financially distressed firm sells permits its demand for permits is downward sloping in permit price. However, if the firm buys permits $(e>l)$, the sign of V_{ep} is indeterminate because its second term is positive. Thus, it is possible that the permit demand function for a firm that simultaneously risks bankruptcy and optimally chooses to buy permits may be upward sloping. As odd as this result appears, it is consistent with a result of Damania and Bulte (2005) who found that an increase in regulatory stringency to induce more conservative harvests in a fishery can lead to less conservative choices by firms that risk bankruptcy. Increased regulatory stringency in our model means that the aggregate cap on emissions is reduced and fewer permits are issued. Under most circumstances we would expect this to increase the price of permits and lead all firms to reduce their emissions. However, a financially distressed firm that is a net buyer of permits may react to the reduced cap on aggregate emissions and increased permit price by increasing its emissions.

1.4 The Initial Allocation of Permits and the Market Effects of Bankruptcy Risk

In this section we examine the market effects of bankruptcy risk and limited liability, particularly the role that the initial allocation of permits plays in determining market outcomes and the allocative efficiency of competitive emissions trading. We focus on the initial permit allocation for two reasons. First, increasing the initial supply of permits to financially distressed firms reduces their risk of bankruptcy, everything else equal. Therefore, we can trace out the effects of varying bankruptcy risk on permit markets by varying the initial allocation of permits. Second, in contrast to the conventional wisdom that the initial permit allocation does not affect the performance of competitive emissions trading, we have just demonstrated that the initial permit allocation will certainly impact emissions markets when some firms risk bankruptcy. Hence, the initial allocation has efficiency consequences that cannot be ignored.

In this section we simplify the analysis by assuming that an emissions trading program contains just two types of firms, 1 and 2. Type 1 firms do not risk bankruptcy while type 2 firms do. There are n_i identical firms of type $i = 1, 2$. Let l_i, e_i and π_i denote the initial allocation of permits, emissions, and expected profit function for each type i firm. The emissions of a type 1 firm is $e_1(p)$, the implicit solution to $p = \pi_1'(e_1)$, which of course is independent of their initial allocation of permits because they do not risk bankruptcy. It is straightforward to show that $e_1(p)$ is monotonically decreasing in p.[6] The emissions choice of a type 2 firm is $e_2(p,l_2)$, the characteristics of which we explored in the previous section.

With an aggregate supply of permits equal to L, the permit market clears if and only if $n_1e_1(p)+n_2e_2(p,l_2)=L$, which implicitly defines the equilibrium price of permits as a function of the total supply of permits and the allocation to the financially distressed firms; that is, $p(L,l_2)$. Differentiate the identity $n_1e_1(p(L,l_2))+n_2e_2(p(L,l_2),l_2)\equiv L$ with respect to l_2 and rearrange the result to obtain the effect of the allocation of permits to the firms that risk bankruptcy on the equilibrium permit price.

$$\frac{\partial p}{\partial l_2}=\frac{-n_2\partial e_2/\partial l_2}{n_1\left(de_1/dp\right)+n_2\left(de_2/dp\right)} \quad . \tag{1.9}$$

The numerator of the right hand side of [1.9] is positive because, as we showed in the last section $\partial e_2/\partial l_2<0$. The denominator of the right hand side of [1.9] is the slope of the aggregate demand function for emissions permits. In general the impact of permit price on the aggregate demand function is indeterminate because of the possibility that financial insecure firms' permit demands increase in the permit price. For most of the rest of analysis we assume that the aggregate demand function for permits is decreasing in the permit price, because we believe this is the most likely case in real applications. We will, however, briefly note the consequences of an upward sloping aggregate demand function at the end of this section. Under the assumption that the denominator of [1.9] is negative, $\partial p/\partial l_2<0$. This indicates that

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[6] From $p-\pi_1'(e_1)=0$ obtain $de_1/dp=1/\pi_1''(e_1)<0$. The sign follows from the strict concavity of $\pi_1(e_1)$.

the equilibrium permit price is increasing as the allocation of permits to financially distressed firms is reduced. Consequently, higher bankruptcy risk in an emissions trading market is likely to produce a higher permit price.

In turn, the higher permit price changes the emissions of financially secure and insecure firms in opposite directions. Since $de_1/dp < 0$, reducing the initial allocation of permits to the financially insecure firms decreases the emissions of the financially secure firms through the increase in the permit price. Holding aggregate emissions to L, then, requires that the equilibrium response of the insecure firms to a decrease in their initial allocation of permits is that they increase their emissions. To demonstrate this formally, note that $(\partial e_2/\partial p)(\partial p/\partial l_2) + \partial e_2/\partial l_2$ is the equilibrium emissions response of a financially distressed firm to a change in the initial permit allocation to these firms. While we have shown that the direct effect, $\partial e_2/\partial l_2$, is less than zero, the sign of the indirect effect, $(\partial e_2/\partial p)(\partial p/\partial l_2)$, is ambiguous because the sign of $\partial e_2/\partial p$ is ambiguous. However, the total effect is negative. To see this substitute [1.9] into $(\partial e_2/\partial p)(\partial p/\partial l_2) + \partial e_2/\partial l_2$ to obtain

$$(\partial e_2/\partial p)(\partial p/\partial l_2) + \partial e_2/\partial l_2 = \frac{n_2(de_1/dp)(\partial e_2/\partial l_2)}{n_1(de_1/dp) + n_2(de_2/dp)} < 0. \quad [1.10]$$

Under the assumption that the aggregate demand for permits is downward sloping, the sign of [1.10] is negative because $de_1/dp < 0$ and $\partial e_2/\partial l_2 < 0$. Therefore, increased bankruptcy risk can increase the number of permits demanded by financially insecure firms, but decrease the number of permits demanded by financially secure firms.

Now let us determine how the initial allocation of permits and bankruptcy risk affects the efficiency of a permit market in terms of its ability to distribute emissions control to minimize the expected aggregate abatement costs. The total abatement costs of the industry can be expressed as

$$TC = n_1[\pi_1(e_1^m) - \pi_1(e_1)] + n_2[\pi_2(e_2^m) - \pi_2(e_2)], \qquad [1.11]$$

where recall that e_1^m and e_2^m are determined by $\pi_1'(e) = 0$ and $\pi_2'(e) = 0$. The cap on aggregate emissions implies $e_1(p(L,l_2) = \left(L - n_2 e_2(p(L,l_2),l_2)\right)/n_1$. Substitute this into [1.11] and differentiate it with respect to l_2 to obtain

$$\partial TC/\partial l_2 = n_2(\pi_1' - \pi_2')\left(\frac{\partial e_2}{\partial p}\frac{\partial p}{\partial l_2} + \frac{\partial e_2}{\partial l_2}\right). \qquad [1.12]$$

Recall that financially secure firms choose their emissions so that $p = \pi_1'(e_1)$, but firms that risk bankruptcy choose their emissions so that $p > \pi_2'(e_2)$. Therefore, $\pi_1' - \pi_2' > 0$ in a market equilibrium. The last term of [1.12] contains the direct and indirect effects of changing l_2 on the emissions of type 2 firms, the combination of which we have just shown to be negative (equation [1.10]). Therefore, $\partial TC/\partial l_2 < 0$ so that the aggregate abatement costs of holding the industry's aggregate emissions to L is decreasing in the initial allocation of permits to firms that risk bankruptcy. Consequently, increased bankruptcy risk in an emissions trading program can increase the expected aggregate abatement costs.

To be complete, let us briefly explain how these results change if the aggregate permits demand function is increasing in the permit price in equilibrium. In this case, a lower permit allocation to financially insecure firms, which means higher bankruptcy risk, actually reduces the equilibrium permit price. Consequently, financially secure firms increase their emissions while insecure firms decrease emissions. Moreover, the sigh of $\partial TC/\partial l_2$ is reversed, indicating that decreasing the allocation of permits to financially insecure firms can reduce the expected aggregate abatement costs of the industry. However, we should be aware that these results only occur at the extreme case where the aggregate demand function of permits is upward sloping.

1.5 Conclusion

Using our results and the monotonic relationship between bankruptcy risk and the initial allocation of permits to financially insecure firms, we have generated several policy-relevant conclusions about the impact of bankruptcy risk on the performance of emissions trading markets. The presence of bankruptcy risk reduces the allocative efficiency of competitive emissions trading markets, and makes the distribution of individual control responsibility dependent on the initial allocation of permits. Thus, the fundamental values of competitive emissions trading programs do not hold when some firms in the market risk bankruptcy. Financial insecurity, like market power and transaction costs, is yet another problem that can prevent emissions markets from fulfilling their theoretical promises. Although we have focused the analysis on emissions trading schemes, these results can be safely generated in other property rights trading markets, such as ITQ.

One may be tempted to use our results to suggest that regulators can use the initial distribution of permits to mitigate the inefficiency associated with bankruptcy risk. But doing so would not be a trivial undertaking. There are difficulties associated with asymmetric information. A regulator must know which firms are in financial distress, which may not be readily available. Perhaps more importantly, firms would have the incentive to exaggerate their bankruptcy risk to obtain a greater allocation of permits. In addition, financially secure firms would very likely object to allocating more permits to insecure firms in the sense that allocating more permits to insecure firms would basically be a subsidy for poorly performing firms. Hence, the regulator has also to decide whether keeping financially distressed firms in the industry is necessary. Finally, using the initial allocation to promote efficient permit markets would have to overcome the tendency to allocate permits by some sort of grandfathering rule.

While we have focused on the performance of tradable permit programs in this paper, our results suggest that the inefficiency associated with bankruptcy risk will also be present in other market-based policies, and may actually be worse. For example, policies with auctioned permits can be viewed as tradable permit programs without freely-given initial permit allocations. Since we've shown a negative relationship between the initial allocation of permits and bankruptcy risk and its associated market inefficiency, an auction, which allocates zero permits to all firms, would seem to maximize the inefficiency associated with bankruptcy risk. An emissions tax would produce the same result. There are good reasons to suspect that auctioning permits or taxing emissions would often be more efficient than freely-allocated permits, which include their ability to produce revenue that can offset distortionary taxes in an economy, and because they may promote more rapid technologic change. However, from the singular perspective of the inefficiency caused by bankruptcy risk, the free allocation of permits to financially distressed firms may be more efficient than other market-based policies that do not have this feature.

There are many other possible extensions of our model and results that are likely to be valuable. Let us mention just a few. While we have focused on a static model of permit trading, modeling bankruptcy risk in dynamic tradable permit markets (that may or may not allow some form of permit banking) would force us to examine the impact of financial insecurity on the efficiency of these markets over time as well as across firms. We have also assumed a fixed number of firms under a tradable property rights regulation. However, financial distress makes the endogeneity of the number of firms in an industry and the associated impacts on permit market efficiency an important area for future work. Finally, while we have assumed that firms fully comply with their output permits, allowing for noncompliance would likely yield interesting insights into the relationship between bankruptcy risk and compliance choices, and how these market difficulties work together to impact the performance of tradable permit programs. Empirical tests of our results would be at least as important as any theoretical extension of our model. Does financial insecurity actually reduce allocative efficiency in tradable permit markets? In the absence of naturally occurring data, testing this hypothesis in a laboratory setting would be a straightforward exercise, and would probably lead to further insights into the relationship between the financial health of firms and the performance of tradable permit markets.

CHAPTER 2

BANKRUPTCY RISK AND IMPERFECTLY ENFORCED EMISSIONS TAXES

2.1 Introduction

As a market-based pollution control policy, emissions taxes have attracted a wide attention in both theoretical world and policy circles since the early 1970's. Under perfect competition a unit Pigouvian tax of emissions, which is equal to the marginal social damage generated by a pollutant, is proved to produce a Pareto-efficient allocation of resources. See Baumol and Oates (1975). Given the difficulties in estimating damage costs a uniform tax chosen by the authority still leads to a reduction in emissions at the least cost possible to the society in the sense that it equates marginal abatement costs among polluters.

However, with limited resources the enforcement of emissions taxes is imperfect and hence leaves firms with the motivation to evade. Harford (1978) was the first effort to study the consequences of evadable pollution taxes. In his work, a unit tax is applied to the reported emissions and penalties for pollution tax evasion are imposed to prevent firms from reporting zero released emissions. It is shown that in equilibrium firms' marginal abatement costs are equal to the unit tax as long as the expected punishment induces positive emissions report. This result implies that the efficiency of emissions taxes carries over to the case with tax evasion. Moreover, the actual level of emissions is independent of enforcement parameters: the penalty on tax evasion and the probability of detection. Consequently, aggregate emissions are insensitive to the enforcement strategies of emissions taxes.

There also exists a sizable literature concerning the imperfect enforcement of another market-based pollution control policy—emissions trading schemes. Malik (1990) noted that as long as the probability of being audited is constant as in the case of random audits, markets for pollution control still generate efficient distributions even with noncompliance. And, actual emissions do not directly depend on the enforcement policy in the case of competitive emissions trading. Using laboratory experiments, Murphy and Stranlund (2006) confirm that the direct effect of monitoring and penalties on emissions choices is zero. Stranlund and Dhanda (1999) show that a firm's level of permit violation, including whether to violate or not, is independent of firm-level characteristics, such as prices of outputs and inputs, production and abatement technologies, etc. This finding has important implications for enforcing emissions trading programs because it suggests that there is no need for regulators to target their enforcement efforts on firm-specific parameters. Murphy and Stranlund (2007) largely support this result by experimental data.

Sandmo (2002) also focuses on the consequences of imperfect enforcement on environmental policies. He explores whether the efficiency of emissions taxes with imperfect enforcement continues to hold in different situations. It is shown that when the probability of detection is endogenous and dependent on actual emissions and reported emissions, tax evasion may destroy the appealing efficiency of emissions taxes. In the case of risk aversion, even though the release of a pollutant reported by noncompliant firms changes emissions taxes could still distribute individual control responsibility efficiently.

In this chapter we discuss another situation under which imperfect compliance may jeopardize the efficiency property of emissions taxes—bankruptcy risk. We examine the features of an imperfectly enforced emissions tax when some regulated firms risk bankruptcy. With the continuing application of pollution taxes, it is natural for regulators to confront situations involving financially distressed firms. Thus, it is important to know how the financial status of regulated firms can impact the performance of emissions taxes. As stated in the chapter 1, we are not the first to show that financial health of firms affects regulations. Spiegel and Spulber (1994) investigate the interactions between the investment and financial decisions of firms and a regulator’s control of their output price. Damania (2000) explores the link between pollution taxes and the financial and output decisions of firms in an oligopolistic industry, but the consequences of noncompliance and the effects of bankruptcy risk on emissions taxes is less of his concern. Damania and Bulte (2005) relate the harvest decisions of firms in a fishery to their financial structure and imperfectly enforced regulatory controls, but they focus on fixed harvest quotas.

We demonstrate that the desirable characteristics of an imperfectly enforced emissions tax disappear when some regulated firms face the risk of bankruptcy. In this case an emissions tax will fail to allocate individual emissions control efficiently. Thus, the main reason for implementing emissions taxes does not hold when some pollution sources risk bankruptcy. Moreover, firms that risk bankruptcy choose higher emissions when they are noncompliant than when they are compliant. Consequently, imperfect enforcement has a negative environmental consequence when some firms risk insolvency that is not present when all firms are financially secure. Finally, financially insecure firms choose higher violations than financially secure firms. Thus, the financial health of firms is an important element in the allocation of scarce enforcement resources among firms. The key factor that produces these negative results is the well-known limited liability effect of debt financing—financially insecure firms ignore returns in bankrupt states because debt holders become the residual claimants. Thus, they make their decisions by optimizing only over states in which they are solvent.

The rest of this chapter is organized as follows. In next section we lay out a model of a firm that operates under an imperfectly enforced emissions tax and that may risk bankruptcy. Because financial security is a special case of this model, we use it in section 3 to review the performance of an emissions task when no firm risks insolvency, particularly the allocative efficiency of emissions taxes, the independence of individual and aggregate emissions on imperfect enforcement, and the independence of firms' violations on their exogenous characteristics. In section 4 we demonstrate how each of these results is modified in the presence of financially insecure firms. We conclude in section 5.

2.2 A Model of an Indebted Firm under an Imperfectly Enforced Emissions Tax

Throughout we consider an industry composed of heterogeneous, risk neutral firms whose emissions are controlled by a uniform emissions tax. Enforcement of the tax is imperfect in the sense that it is not sufficient to keep firms from attempting to evade a portion of their tax liabilities. Assume the manager of each firm is controlled by shareholders, so the manager of each firm seeks to maximize the expected value of the firm.

For a particular firm in the industry, given its optimal choices of inputs and outputs, the gross profit of the firm (profit excluding its tax and penalty payments) is $\pi(e,\beta)(1+z)$, where e is the firm's emissions, β is an exogenous factor that affects the firm's gross profit, and z is a continuous random variable that is independently, but not necessarily identically distributed among the firms in the industry. Each firm's gross profit function is strictly increasing and strictly concave in the firm's emissions. The random variable z captures the effects of uncertainty on the firm's gross profit, such as the effects of random shifts in the demand for its output or in factor prices. The probability density function of z is $g(z)$ with support $[\underline{z},\overline{z}]$. The expectation of z is zero so that the firm's expected gross profit is simply $\pi(e,\beta)$. The value of z is revealed only after the firm has made its emissions and compliance decisions.

Each firm's reported emissions, r, are taxed at rate t. To check whether the firms report their true emission, each of them is audited with a constant probability α that is common knowledge between the regulator and the firm. An audit reveals a firm's actual emissions without errors. A firm is in violation if its actual emissions exceed its reported emissions. Since we are concerned with the combined roles of financial insecurity and noncompliance in this paper we limit our analysis to situations in which a firm's violation is positive. If an audit reveals that a firm is in violation, a penalty $f(e-r)$ is imposed. The penalty function is the same for all firms, and it is positive, strictly increasing, and strictly convex for positive violations.

Like Brander and Lewis (1986), Damania (2000), Damania and Bulte (2005), we focus the analysis on a single period in which the financial structure of the firm is fixed. A firm's financial structure is summarized by two variables. One is the firm's equity A, and the other is the firm's debt obligation D. The firm reimburses creditors from net profits. If the firm's losses exceed its equity, it will declare bankruptcy, shut down, and use its equity to partially pay off its debt. Apart from losing its equity A, there are no other costs associated with declaring bankruptcy.

Given a realization of z, the payoff to the shareholders of the firm is

$$\pi(e,\beta)(1+z)-tr-f(e-r)-D+A, \tag{2.1}$$

if it is audited by the regulator, and the payoff is

$$\pi(e,\beta)(1+z)-tr-D+A, \tag{2.2}$$

if the firm is not audited. From [2.1] and [2.2] we define two critical breakeven states of the random variable z in which the firm is indifferent between staying in business and ceasing production. If the firm is audited, the breakeven value of z, denoted as z^a, is determined by setting [2.1] equal to zero and solving for z, yielding

$$z^a=\frac{tr+f(e-r)+D-A}{\pi(e,\beta)}-1. \tag{2.3}$$

The breakeven value of z when the firm is not audited is denoted z^{na}, and determined by setting [2.2] equal to zero and solving for z:

$$z^{na}=\frac{tr+D-A}{\pi(e,\beta)}-1. \tag{2.4}$$

Note that $z^{na} < z^{a}$ when the firm is noncompliant (i.e., $e - r > 0$), and $z^{na} = z^{a}$ when the firm is compliant ($e = r$). If the realized value of z is greater than both z^{a} and z^{na} the firm will be solvent whether it is audited or not, but if the realized value of z is less than both z^{a} and z^{na} the firm will be insolvent regardless of monitoring. If the firm is noncompliant and the realized value of z is between z^{a} and z^{na}, then the firm remains solvent if it is not audited, but is bankrupt if it is audited.

Note that $\int_{z^{a}}^{\bar{z}} g(z)dz$ and $\int_{z^{na}}^{\bar{z}} g(z)dz$ are probabilities the firm stays in business when it is audited and when it is not, respectively. Clearly, these probabilities decrease with z^{a} and z^{na}. Thus, if $z^{na} \leq z^{a} \leq \underline{z}$, then $\int_{z^{a}}^{\bar{z}} g(z)dz = \int_{z^{na}}^{\bar{z}} g(z)dz = 1$, indicating that the firm is financially secure in the sense that it does not risk bankruptcy. However, at the other end of the range of z, if $\bar{z} \leq z^{na} \leq z^{a}$, then $\int_{z^{a}}^{\bar{z}} g(z)dz = \int_{z^{na}}^{\bar{z}} g(z)dz = 0$ and the firm will definitely go bankrupt. In this case it will not even bother to begin production. Despite this possibility, and the possibility that a firm will certainly be insolvent if it is audited but may not be if it is not audited, we simplify our analysis by assuming that the probabilities the firm is solvent are strictly greater than zero. This requires $z^{na} \leq z^{a} < \bar{z}$.

We are now ready to specify the decision problem of the manager of a firm. Recall that a manager is risk neutral and chooses his or her firm's emissions and emissions report to maximize the expected value of the firm. Assuming that the manager chooses positive emissions report, and violation, his or her decision problem is to choose e and r to maximize

$$
\begin{aligned}
V = \alpha & \left\{ \int_{\underline{z}}^{z^a} (-A) g(z) dz + \int_{z^a}^{\bar{z}} \left[\pi(e,\beta)(1+z) - tr - f(e-r) - D \right] g(z) dz \right\} \\
& + (1-\alpha) \left\{ \int_{\underline{z}}^{z^{na}} (-A) g(z) dz + \int_{z^{na}}^{\bar{z}} \left[\pi(e,\beta)(1+z) - tr - D \right] g(z) dz \right\}.
\end{aligned} \qquad [2.5]
$$

The firm's expected value function consists of two parts; the firm's expected value given that it is audited multiplied by the probability of an audit (the top line of V) plus the expected value of the firm given that it is not audited times the probability that it is not audited (the bottom line of V). It is important to note that shareholder-controlled financially insecure firms consider the states of bankruptcy when making decisions only because their equity is at stake. But the level of equity is fixed. This is the essence of the limited liability effect, which has important consequences for the choices of a firm that operates under an emissions tax.

To determine these choices we assume throughout that V is strictly concave in e and r. Therefore, the following first-order conditions are both necessary and sufficient to identify a firm's optimal emissions and emissions report:

$$
\begin{aligned}
V_e = \alpha & \left\{ \int_{z^a}^{\bar{z}} \left[\pi_e(e,\beta)(1+z) - f'(e-r) \right] g(z) dz - z_e^a g(z^a) \left[\pi(e,\beta)(1+z^a) - tr - f(e-r) - D + A \right] \right\} \\
& + (1-\alpha) \left\{ \int_{z^{na}}^{\bar{z}} \pi_e(e,\beta)(1+z) g(z) dz - z_e^{na} g(z^{na}) \left[\pi(e,\beta)(1+z^{na}) - tr - D + A \right] \right\} = 0; \\
V_r = \alpha & \left\{ \int_{z^a}^{\bar{z}} \left[f'(e-r) - t \right] g(z) dz - z_r^a g(z^a) \left[\pi(e,\beta)(1+z^a) - tr - f(e-r) - D + A \right] \right\} \\
& + (1-\alpha) \left\{ \int_{z^{na}}^{\bar{z}} (-t) g(z) dz - z_r^{na} g(z^{na}) \left[\pi(e,\beta)(1+z^{na}) - tr - D + A \right] \right\} = 0.
\end{aligned}
$$

Recall that z^a and z^{na} are determined from

$\pi(e,\beta)(1+z^a) - tr - f(e-r) - D + A = 0$ and $\pi(e,\beta)(1+z^{na}) - tr - D + A = 0$, respectively. Using these relationships to simplify $V_e = 0$ and $V_r = 0$ yields:

$$V_e = \pi_e(e,\beta)\left[\alpha\int_{z^a}^{\bar{z}}(1+z)g(z)dz + (1-\alpha)\int_{z^{na}}^{\bar{z}}(1+z)g(z)dz\right]$$
$$-\alpha f'(e-r)\int_{z^a}^{\bar{z}}g(z)dz = 0 \quad [2.6]$$

$$V_r = \alpha f'(e-r)\int_{z^a}^{\bar{z}}g(z)dz - t\left[\alpha\int_{z^a}^{\bar{z}}g(z)dz + (1-\alpha)\int_{z^{na}}^{\bar{z}}g(z)dz\right] = 0\,. \quad [2.7]$$

Now combine equations [2.6] and [2.7] to obtain

$$\left[\pi_e(e,\beta)-t\right]\left[\alpha\int_{z^a}^{\bar{z}}g(z)dz + (1-\alpha)\int_{z^{na}}^{\bar{z}}g(z)dz\right]$$
$$+\pi_e(e,\beta)\left[\alpha\int_{z^a}^{\bar{z}}zg(z)dz + (1-\alpha)\int_{z^{na}}^{\bar{z}}zg(z)dz\right] = 0. \quad [2.8]$$

Our analysis of the effects of bankruptcy risk on imperfectly enforced emissions taxes is based on equations [2.7] and [2.8].

2.3 Imperfectly Enforced Emissions Taxes When Firms Are Financially Secure

In this section we use our model to review some fundamental conclusions about imperfectly enforced emissions taxes when firms do not risk bankruptcy. There are no new results in this section—some have been shown directly by Harford (1978 and 1987) and Sandmo (2002), in particular, while others can be gleaned from the works of Malik (1990) and Stranlund and Dhanda (1999) who focused on emissions trading. These results have to do with the allocative efficiency of an imperfectly enforced tax, that individual and aggregate emissions do not depend on whether a tax is enforced perfectly or not, and the independence of violations on firm-level characteristics. We present all of the results in a single proposition.

Proposition 1: If no firm that operates under an emissions tax risks bankruptcy, then:

(1) The allocation of individual emissions control is efficient despite imperfect enforcement.

(2) Each firm's choice of emissions is independent of their compliance decision.

(3) Aggregate emissions are unaffected by imperfect enforcement.

(4) Individual firm's violations are independent of its exogenous characteristics.

Proof of Proposition 1: If a firm does not risk bankruptcy then $z^{na} \leq z^{a} \leq \underline{z}$, which implies $\int_{z^a}^{\bar{z}} g(z)dz = \int_{z^{na}}^{\bar{z}} g(z)dz = 1$ and $\int_{z^a}^{\bar{z}} zg(z)dz = \int_{z^{na}}^{\bar{z}} zg(z)dz = 0.$ The latter relationships are due to our assumption that the expectation of z is equal to zero. Now substitute these into equations [2.7] and [2.8] to obtain $t = \alpha f'(e-r)$ and $\pi_e(e,\beta) = t$, respectively. Allocative efficiency requires that the industry's expected gross profit be maximized given the level of aggregate emissions that is induced by the emissions tax[7]. As is well-known the necessary conditions for this maximization problem imply that the firms' marginal expected gross profits are equal. This is achieved because $\pi_e(e,\beta) = t$ for every firm, each firm faces the same emissions tax, and hence, $\pi_e(e,\beta)$ is equal for every firm. This proves part (1) of the proposition. To prove part (2) note that a firm's choice of emissions is $e(t,\beta)$, the implicit solution to $\pi_e(e,\beta) = t$. Since this decision does not depend on monitoring or penalties, it is independent of the firm's compliance decision. Part (3) follows directly from part (2): if individual firms' emissions are unaffected by imperfect enforcement, aggregate emissions are unaffected as well. To prove part (4), write the firm's optimal emissions report as $r(\beta)$. (Writing the firm's report in this way is not meant to suggest that it only depends on β — it also depends on the emissions tax,

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[7] This is fully equivalent to minimizing the aggregate abatement costs of holding an industry to a specific level of aggregate emissions.

monitoring, and the penalty function). Given the firm's optimal choice of emissions, $e(t,\beta)$, and $t = \alpha f'(e-r)$ we have $t - \alpha f'(e(t,\beta) - r(\beta)) \equiv 0$. Differentiate this with respect to β to obtain $-\alpha f''(\cdot)(e_\beta - r_\beta) = 0,$ which implies that the marginal effect on the firm's violation of a change in β is $e_\beta - r_\beta = 0,$ which indicates that the firm's choice of violation is independent of β. Thus, the individual violations of financially secure firms are independent of their exogenous differences, suggesting that a regulator finds no value in targeting its enforcement effort. The proof is complete. QED.

Before we move to examining how these results change when at least some firms in an industry risk bankruptcy, it is worthwhile to be clear about how the results depend on two assumptions we maintain throughout this paper. The first is that each firm submits a positive emissions report. It is straightforward to show that a financially secure firm that reports zero emissions chooses its actual emissions so that $t \geq \pi_e(e,\beta).$ If this inequality is strict for some firms, then the expected marginal gross profits of the firms will not be equalized and aggregate expected gross profits will not be maximized. The possibility that a tax regulation will be so poorly enforced that some firms report zero emissions seems rather remote. One may also wonder whether a real firm would ever reports zero emissions, given that this would send such an obvious signal of noncompliance to the regulator.

The other assumption that is necessary for Proposition 1 is that the probability a firm will be monitored does not depend on its emissions or emissions report. Actually, all that is needed for Proposition 1 to hold is that firms are not monitored with probability $\alpha(e,r)$ such that $\alpha_e \neq -\alpha_r$ (Harford 1978 and 1987, Sandmo 2002). Under such a monitoring probability firms will choose their emissions so that their expected marginal gross profits differ from the tax. This will cause expected aggregate gross profit to be less than maximum. For this reason, we do not examine such a monitoring strategy in this paper.

2.4 Imperfectly Enforced Emissions Taxes When Firms Are Financially Insecure

In this section we demonstrate how each of the results in Proposition 1 is modified in the presence of financially insecure firms. We begin with the allocative efficiency of an emission tax when some firms in an industry risk bankruptcy.

Proposition 2: If some firms under an emissions tax risk bankruptcy the distribution of individual emissions control will not be efficient.

Proof of Proposition 2: Rearrange equation [2.8] to obtain

$$\frac{-\left[\pi_e(e,\beta)-t\right]}{\pi_e(e,\beta)} = \frac{\alpha\int_{z^a}^{\bar{z}} zg(z)dz + (1-\alpha)\int_{z^{na}}^{\bar{z}} zg(z)dz}{\alpha\int_{z^a}^{\bar{z}} g(z)dz + (1-\alpha)\int_{z^{na}}^{\bar{z}} g(z)dz}. \qquad [2.9]$$

On the right hand side of [2.9], the denominator is positive because $\int_{z^a}^{\bar{z}} g(z)dz > 0$ and $\int_{z^{na}}^{\bar{z}} g(z)dz > 0$. The numerator is also positive. To understand why, recall that the expectation of z is zero so that $\int_{\underline{z}}^{\bar{z}} zg(z)dz = 0$. Since the firm risks bankruptcy, at least when it is audited, $\underline{z} < z^a$, implying $\int_{z^a}^{\bar{z}} zg(z)dz > 0$. If the firm is definitely solvent when it is not audited, $z^{na} \leq \underline{z}$ and $\int_{z^{na}}^{\bar{z}} zg(z)dz = 0$. If the firm risks insolvency when it is not audited, $\underline{z} < z^{na}$ and $\int_{z^{na}}^{\bar{z}} zg(z)dz > 0$. Since $\int_{z^{a}}^{\bar{z}} zg(z)dz > 0$ and $\int_{z^{na}}^{\bar{z}} zg(z)dz \geq 0$ the numerator of the right side of [2.9] is strictly positive, implying further that the entire right side of [2.9] is positive.

Given that the right side of [2.9] is positive, the equality holds if and only if the left side is positive as well. Note that this will be true if and only if $\pi_e(e,\beta) > 0$ and $\pi_e(e,\beta) < t$. Recall that allocative efficiency requires that each firm choose its emissions so that its expected marginal gross profit is equal to the tax. Since financially insecure firms choose their emissions so that $\pi_e(e,\beta) < t$ while those that are financially secure choose their emissions so that $\pi_e(e,\beta) = t$, the distribution of emissions in an industry that contains financially insecure firms will not be efficient. QED.

Note that not only will the expected marginal gross profits of firms that risk bankruptcy differ from those of firms that are financially secure, expected marginal gross profits among financially distressed firms will likely differ because the values of z^a and z^{na} vary among these firms, and the densities $g(z)$ may vary as well. Since the emissions tax will not equate the firms' expected marginal gross profits, expected industry gross profit will not be maximized. Thus, the main reason for implementing emissions taxes does not hold in situations involving financially insecure firms.

The result that firms that risk bankruptcy choose their emissions so that their expected marginal gross profits are less than the tax implies that they choose higher emissions than if they were financially secure. This is due to the limited liability effect—since firms that risk bankruptcy do not consider bankrupt states in their decisions they optimize over only those states in which they will be solvent. Optimization over a restricted range of the random variable z causes them to choose higher emissions.

It is important to note that this result of allocative inefficiency holds whether financially insecure firms are also noncompliant or not. We have shown in Chapter 1 that emissions trading programs with perfect enforcement are inefficient in the existence of financially distressed firms. With the next proposition we show that imperfect enforcement causes financially insecure firms to choose even higher levels of emissions.

Proposition 3: A firm that risks bankruptcy will choose higher emissions if an emissions tax is imperfectly enforced than if it is perfectly enforced.

Proof of Proposition 3: When an emissions tax is perfectly enforced, a firm chooses its emissions to equal its reported emissions ($e = r$). From [2.3] and [2.4], compliance implies $z^a = z^{na}$. Under this condition the firm's expected value function [2.5] simplifies to

$$V\left(e, z^a = z^{na}\right) = \int_{\underline{z}}^{z^{na}} (-A)g(z)dz + \int_{z^{na}}^{\bar{z}} \left[\pi(e,\beta)(1+z) - te - D\right]g(z)dz \,,$$

and its optimal choice of emissions satisfies

$$V_e\left(e, z^a = z^{na}\right) = \left[\pi_e(e,\beta) - t\right]\int_{z^{na}}^{\bar{z}} g(z)dz + \pi_e(e,\beta)\int_{z^{na}}^{\bar{z}} zg(z)dz = 0 \,. \quad [2.10]$$

Suppose on the other hand that the emissions tax is imperfectly enforced so that the firm is noncompliant. Suppose further that when the firm is noncompliant it chooses emissions $\overline{e}$ to satisfy equation [2.8]. The proof of the proposition is based on evaluating the sign of $V_e\left(e,z^a=z^{na}\right)$ at $\overline{e}$ and using the strict concavity of $V\left(e,z^a=z^{na}\right)$ in e to show that the firm's choice of emissions when it is compliant is less than $\overline{e}$.

Using [2.10], $V_e\left(e,z^a=z^{na}\right)$ evaluated at $\overline{e}$ is

$$V_e\left(\overline{e},z^a=z^{na}\right)=\left[\pi_e(\overline{e},\beta)-t\right]\left[\int_{z^{na}(\overline{e})}^{\overline{z}}g(z)dz\right]+\pi_e(\overline{e},\beta)\left[\int_{z^{na}(\overline{e})}^{\overline{z}}zg(z)dz\right]. \quad [2.11]$$

That $\overline{e}$ satisfies equation [2.8] allows us to write it as the identity

$$\begin{aligned}&\left[\pi_e(\overline{e},\beta)-t\right]\left[\alpha\int_{z^a(\overline{e})}^{\overline{z}}g(z)dz+(1-\alpha)\int_{z^{na}(\overline{e})}^{\overline{z}}g(z)dz\right]\\&\qquad+\pi_e(\overline{e},\beta)\left[\alpha\int_{z^a(\overline{e})}^{\overline{z}}zg(z)dz+(1-\alpha)\int_{z^{na}(\overline{e})}^{\overline{z}}zg(z)dz\right]\equiv 0.\end{aligned} \quad [2.12]$$

Use [2.12] to substitute for $\pi_e(\overline{e},\beta)-t$ in [2.11] and rearrange terms to show that

$$\begin{aligned}&V_e\left(\overline{e},z^a=z^{na}\right)\\&=\pi_e(\overline{e},\beta)\frac{\alpha\left[\int_{z^{na}(\overline{e})}^{\overline{z}}zg(z)dz\int_{z^a(\overline{e})}^{\overline{z}}g(z)dz-\int_{z^{na}(\overline{e})}^{\overline{z}}g(z)dz\int_{z^a(\overline{e})}^{\overline{z}}zg(z)dz\right]}{\alpha\int_{z^a(\overline{e})}^{\overline{z}}g(z)dz+(1-\alpha)\int_{z^{na}(\overline{e})}^{\overline{z}}g(z)dz}.\end{aligned} \quad [2.13]$$

From the proof of Proposition 2, $\pi_e(\overline{e},\beta)>0$. The denominator of [2.13] is also positive, so the sign of $V_e\left(\overline{e},z^a=z^{na}\right)$ is equal to the sign of the term in hard brackets. Rearrange this term to show that it has the same sign as

$$\frac{\int_{z^{na}(\overline{e})}^{\overline{z}}zg(z)dz}{\int_{z^{na}(\overline{e})}^{\overline{z}}g(z)dz}-\frac{\int_{z^a(\overline{e})}^{\overline{z}}zg(z)dz}{\int_{z^a(\overline{e})}^{\overline{z}}g(z)dz}. \quad [2.14]$$

The first term of this difference is the conditional expectation of z given $z\in[z^{na}(\overline{e}),\overline{z}]$, while the second is conditional expectation of z given

$z \in [z^a(\overline{e}), \overline{z}]$. Since $z^{na}(\overline{e}) < z^a(\overline{e})$ because the firm is noncompliant at $\overline{e}$, the first term is less than the second and [2.14] is negative. Since [2.14] has the same sign as $V_e\left(\overline{e}, z^a = z^{na}\right)$, $V_e\left(\overline{e}, z^a = z^{na}\right) < 0.$

The firm's optimal choice of emissions given that it is compliant is the solution to $V_e\left(e, z^a = z^{na}\right) = 0.$ Since $V_e\left(e, z^a = z^{na}\right)$ is monotonically decreasing in e and $V_e\left(\overline{e}, z^a = z^{na}\right) < 0$, the firm's choice of emissions when it is compliant is less than if it was noncompliant. Thus, imperfect enforcement causes a firm that risks bankruptcy to choose higher emissions. QED.

Since imperfect enforcement causes financially insecure firms to choose higher emissions than if the tax was enforced so that the firms were compliant, the following proposition follows immediately.

Proposition 4: Imperfect enforcement of an emissions tax leads to higher aggregate emissions when some firms under the risk of bankruptcy.

Recall from Proposition 1 that, under reasonable circumstances, imperfect enforcement has no effect on the emissions of financially secure firms. Thus, a regulator does not need to be concerned about the environmental impacts of imperfect enforcement. However, Proposition 4 reveals that this result does not hold when an emissions tax is applied to firms that risk insolvency—imperfect enforcement weakens the ability of an emissions tax to improve environmental outcomes when it is applied in a situation involving financially insecure firms.

Bankruptcy risk and imperfect enforcement also makes the allocation of enforcement effort more complicated. Part (4) of Proposition 1 reveals that differences in the violations of financially secure firms are independent of differences in their exogenous characteristics. Thus, a regulator does not need to gather information about individual firms to target its enforcement effort—only the tax and the enforcement parameters, all of which are known by the regulator, determine a firm's violations. This is no longer true when some firms risk insolvency. In particular, the violations of financially insecure firms will differ from the violations of financially secure firms.

Proposition 5: Noncompliant firms that risk bankruptcy choose higher violations than if they were financially secure.

Proof of Proposition 5: Define $M = \left[\alpha\int_{z^a}^{\bar{z}} g(z)dz + (1-\alpha)\int_{z^{na}}^{\bar{z}} g(z)dz\right] \Big/ \int_{z^a}^{\bar{z}} g(z)dz$. Use M to rewrite [2.7] as $\alpha f'(e-r) = tM$. If the firm does not risk bankruptcy, $z^{na} < z^a \leq \underline{z}$, which implies $\int_{z^a}^{\bar{z}} g(z)dz = \int_{z^{na}}^{\bar{z}} g(z)dz = 1$ and $M = 1$. Thus, as we showed in the proof of Proposition 1, a noncompliant financially secure firm chooses its violation so that $\alpha f'(e-r) = t$.

On the other hand, if a noncompliant firm risks bankruptcy, $\int_{z^a}^{\bar{z}} g(z)dz < \int_{z^{na}}^{\bar{z}} g(z)dz$. Since the numerator of M is a linear combination of $\int_{z^a}^{\bar{z}} g(z)dz$ and $\int_{z^{na}}^{\bar{z}} g(z)dz$, the fact that the former is less than the latter implies $\alpha\int_{z^a}^{\bar{z}} g(z)dz + (1-\alpha)\int_{z^{na}}^{\bar{z}} g(z)dz > \int_{z^a}^{\bar{z}} g(z)dz$ and $M > 1$. Therefore, a noncompliant financially insecure firm chooses its violation so that $\alpha f'(e-r) > t$. Since $f(e-r)$ is strictly convex, this implies that a noncompliant firm that risks bankruptcy chooses a higher violation than if it did not risk bankruptcy. QED

Armed with Proposition 5, a regulator who is motivated to use its scarce enforcement resources to detect and punish firms that tend toward higher violations may wish to target its enforcement effort at financially insecure firms. Doing so, of course, requires the regulator to gather information on the financial health of all firms. At best, gathering this information will add to the cost of enforcing an emissions tax. Moreover, the higher aggregate violations that are produced by bankruptcy risk and imperfect enforcement may lead to higher costs of sanctioning noncompliant firms. Thus, it may very well be the case that bankruptcy risk places more pressure on scarce enforcement resources.

Note that we have not addressed the point of part (4) of Proposition 1 directly. There we showed the independence of parametric differences in firms' profit functions on differences in their violations. Proposition 5 focuses on the role that differences in the financial health of firms have on differences in their violations. The comparative static relating a parametric change in a financially insecure firm's profit to its violation choice is a very complicated function that has an indeterminate sign. (The derivation of this comparative static is available upon request). Thus, the violations of firms that risk bankruptcy are not, in general, independent of parametric differences in their gross profit functions; in fact, a parametric increase in a firm's profit function can cause it to choose higher or lower violations. Moreover, the comparative static depends on all the parameters of the firm's decision problem, including those involving the enforcement strategy it faces, its financial structure, and the uncertainty about its ultimate profit. Since most of these factors involve information that is likely to be hidden, a regulator will have a very hard time targeting its enforcement effort based on information that determines a firm's profit function.

2.5 Conclusions

We have examined the combined roles of bankruptcy risk and imperfect enforcement on the performance of an emissions tax. In the absence of bankruptcy risk in a population of regulated firms, emissions taxes retain their beneficial characteristics even when they are not enforced perfectly. Under favorable, but not unrealistic conditions, an imperfectly enforced emissions tax produces an efficient allocation of individual emissions control; the aggregate level of control is the same as under a perfectly enforced tax, and differences in individual violations are independent of firm-level differences. All of these characteristics disappear when some firms under an emissions tax risk bankruptcy—the allocation of emissions control is inefficient, imperfect enforcement causes higher aggregate emissions, and financially insecure firms choose higher violations. Thus, the combined effects of bankruptcy risk and imperfect enforcement produce higher expected aggregate costs of emissions control (or rather, lower aggregate expected gross profits), worse environmental quality, and more pressure on scarce enforcement resources.

Regulatory options to limit these losses are probably limited to options that reduce the risks of bankruptcy among financially insecure firms. One option, which was explored by Damania and Bulte (2006) is to provide direct subsidies to distressed firms. This option is fraught with difficulties, including the political difficulty of subsidizing polluting firms, and the moral hazard problem that would surely result because firms would have an incentive to exaggerate their risk of bankruptcy to obtain the subsidy. A more reasonable option might be to allow firms to pollute up to a certain level for free before the tax kicks in. This would reduce firms' tax payments thereby reducing the bankruptcy risk of financially insecure firms, and likely lead to more efficient outcomes. In Chapter 1 we noted that providing a greater number of free tradable emissions permits to insecure firms improved their financial health and led to a more efficient distribution of individual emissions choices.

It may also be possible to use tax rates and enforcement stringency to achieve more efficient outcomes. However, determining how this can be done requires determining the comparative statics of how changes in the tax, monitoring, and penalties affect firms' choices of emissions and violations, and these comparative statics in our model always have indeterminate signs. As others in this literature have found, changing regulatory controls and their enforcement can lead to seemingly paradoxical results; for example, higher emissions taxes can cause financially distressed firms to increase their emissions, and reducing enforcement stringency can promote greater compliance. We should also note that these results depend on the private information of firms, including information about their profit functions and their financial health. This, even though one can imagine that regulators could minimize the inefficiencies associated with bankruptcy risk with judicious choices of tax rates and enforcement strategies, the information requirements of doing so are quite severe.

APPENDIX: CONDITIONAL EXPECTATION

Here we prove that $\int_{\hat{z}}^{\bar{z}} zg(z)dz \Big/ \int_{\hat{z}}^{\bar{z}} g(z)dz$ is the expectation of z conditional on the firm being solvent. The expectation of z conditional on the firm being solvent can be expressed as $E(z \mid z > \hat{z}) = \int_{\hat{z}}^{\bar{z}} z[g(z) \mid z > \hat{z}]dz$, where $g(z) \mid z > \hat{z}$ is the conditional probability density function of z—the density function of z given $z > \hat{z}$. We derive this conditional density function by obtaining the conditional cumulative density function of z, $G(z) \mid z > \hat{z}$.

$$G(z) \mid z > \hat{z} = P(z \le m \mid z > \hat{z}) = \frac{P(\hat{z} < z \le m)}{P(z > \hat{z})} = \frac{P(z \le m) - P(z \le \hat{z})}{P(z > \hat{z})} \qquad \text{[A.1]}$$

In [A.1], m is a random point chosen in $(\hat{z}, \bar{z}]$. We get the conditional probability density function of z by differentiating [A.1] with respect to m. Note that $P(z \le m)$ is exactly the cumulative density function of z, i.e., $G(z)$, whose derivative with respect to m is $g(z)$. Thus, $g(z) \mid z > \hat{z} = \dfrac{g(z)}{\int_{\hat{z}}^{\bar{z}} g(z)dz}$ and

$$E(z \mid z > \hat{z}) = \int_{\hat{z}}^{\bar{z}} z[g(z) \mid z > \hat{z}]dz = \frac{\int_{\hat{z}}^{\bar{z}} zg(z)dz}{\int_{\hat{z}}^{\bar{z}} g(z)dz}.$$

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