Environment and Development Economics 10: 435–452 © 2005 Cambridge University Press
doi:10.1017/S1355770X05002287 Printed in the United Kingdom

Environmental regulation and the optimal location of the risk-averse firm under uncertainty

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ABSTRACT. The interrelationships between environmental regulations and firm location are essential features of economic development. This paper examines the optimal location of a competitive firm in response to environmental costs imposed by the abatement investment and taxes when the cost of the environmental regulation varies spatially under uncertainty. It contributes to the literature by incorporating the spatial setting into a risk-averse firm's location decision in the presence of environmental regulation uncertainty. An augmented cost of the abatement, input tax, or emission tax causes the risk-averse firm to locate closer to the output market. Uncertainty about environmental regulations also leads a risk-averse firm to locate closer to the output market. Policy implications of the results are discussed. The results have implications for the design and implementation of environmental and other development-related policies, environment–development debate, and trade–environment debate.

1. Introduction

The location choice of firms has important implications for the trade–environment debate, environment–development debate, and future development of various industries. Knowing the possible trends in firm location improves our ability to formulate public policies affecting industry development, respond to the environmental problems of firm concentration in certain areas, and improve trade and economic development policies that consider the impacts of environmental policies. The interrelationship between environmental regulations and industrial location is an essential feature of economic development for developing countries. Therefore, it is important to examine how various policies would impact firms' location decisions. Environmental regulations in the form of abatement investment and market-based policies such as emission taxes and uncertainty about their implementation may affect firm location decisions. As government regulations are imposed to improve environmental quality, there might be changes in the production of goods and spatial locations of firms across regions and countries. This will affect trade flows, economic development, and competitiveness of developing countries.

Environmental regulation and the added costs associated with compliance are considerations often factored into the choice of business location (Bartik, 1988; Jeppesen *et al.*, 2002; Jeppesen and Folmer, 2001). Although national environmental policies have raised the minimum levels of environmental standards, important differences in state and national environmental policies remain. In the United States, state regulations governing hazardous waste disposal, wetlands filling, air and water pollution, and wildlife protection vary considerably (Meyer, 1995). There are also significant differences in the stringency of environmental regulation in several countries. A key concern for developed countries is that developing countries could try to lure investment by lowering or not enforcing their environmental standards (Wheeler, 2001). There is well-documented relative growth of pollution-intensive industries in developing countries. Geographic variation in environmental regulations can induce migration of industries across state or national boundaries to 'pollution havens', where compliance costs associated with environmental regulations are lower (Jeppessen *et al.*, 2002; Bommer, 1999). Analysis of how spatial variability of environmental regulation across states or countries can affect firm location may provide some insight into the pollution haven phenomenon.

The firm location decision is central to the trade–environment debate and environment–development debate (UNCTAD, 1997; Rauscher, 1995). It has an international context, with concerns about companies shifting investment from developed countries to developing countries. Analyzing the firm location decision may shed some light on the effects of environmental regulation in the international arena (OECD, 1994). Proposals to harmonize environmental standards across international boundaries add to the urgency of the question, because of concerns that trade liberalization could induce increased investment in countries with lower environmental standards (Nordstrom and Vaughan, 1999; Dean, 2002). In fact, the possibility of individual firms relocating in response to environmental costs has been a concern for public policy in many countries. The possibility of US manufacturing plants relocating to Mexico was an important issue in the North American Free Trade Agreement debate. Also, current trade liberalization discussions between developed and developing countries have focused on the environmental standards. This paper analyzes the optimal location of the firm in response to the spatially varying environmental regulation costs under uncertainty.

Existing spatial variability of environmental regulations would create opportunities for firms to locate to places with relatively lax environmental regulations. Most firms make their production and location decisions under various sources of uncertainty. Production is often subject to uncertainty about weather or other factors that cannot be controlled by firms. Firms are also faced with uncertainty about environmental regulations. Uncertainty about environmental regulations in the form of either abatement investment or taxes arises because seemingly random changes in government policies make economic decisions risky. Additionally, the environmental policies do not have to change to make the firm's production and location decisions uncertain. Merely discussions in Congress, the administration and the media of potential policy changes introduce some elements of risk into firm planning (Isik, 2004).[1] Thus, uncertainty about the imposition of environmental regulations or liabilities makes the costs of the regulations uncertain, which may affect the optimal production and location decisions of firms.

The purpose of this paper is to examine the impacts of environmental regulations on a risk-averse firm's production and location decisions under uncertainty about technology (production) and environmental regulation. It develops a theoretical model of firm decision making by extending a spatial location model to analyze the extent to which the introduction of environmental regulations affects a risk-averse firm's location decision under uncertainty. The paper also aims at providing a systematic analysis of a risk-averse firm's responses to various market-based policies, such as output, input, and emission taxes, and the implications of spatially varying environmental regulations for location decisions and the environment–development debate.

Much of the literature in environmental economics, public finance, and international trade abstract from the location decisions of firms under uncertainty. A number of studies explored the implications of risk aversion on a firm's production and location decisions in a non-spatial context (Sandmo, 1971; Briys and Eeckhoudt, 1985; Isik, 2002) and in a spatial context (Alperovich and Katz, 1983; Hsu and Tan, 2001; Katz, 1984; Mai, 1984; Mathur, 1983; Park and Mathur, 1988; Park and Mathur, 1990; Tan, 2003). However, there has been little attention given to the implications of uncertainty and risk aversion on a firm's location in the presence of environmental regulations. A few theoretical studies examined the impacts of environmental regulation uncertainty on the location decisions of risk-neutral firms.[2] Xepapadeas (1999) analyzed risk-neutral firms' abatement investment and location responses to environmental policies, which takes the form of emission taxes or tradable emission permits and subsidies. Similarly, Verbeke and De Clercq (2002) examined the relocation of a risk-neutral monopolist under various assumptions with respect to the difference in environmental policy between the home and foreign country. None of these studies, however, examined the impact of environmental policy uncertainty on a risk-averse firm's location decision.

This paper contributes to the literature by incorporating the spatial setting into a model of firm location and production to analyze the spatial effects of environmental regulations on a risk-averse firm's location decision and to obtain comparative statics results with respect to the level of environmental regulation uncertainty. The paper also examines the implications of firm

[1] For example, the differences in the scope, degree, and timing of current and proposed emissions control regulations have made power generation company compliance planning problematic by adding substantial uncertainty about elimination of future fuel flexibility and orderly power plant retirement and replacement (EPRI, 2003).

[2] A few theoretical and empirical studies also examined the impacts of the environmental regulation on the location of risk-neutral firms under certainty (Bommer, 1999; Jeppesen *et al.*, 2002; Motta and Thisse, 1994). However, these studies did not focus on the impact of environmental regulation uncertainty.

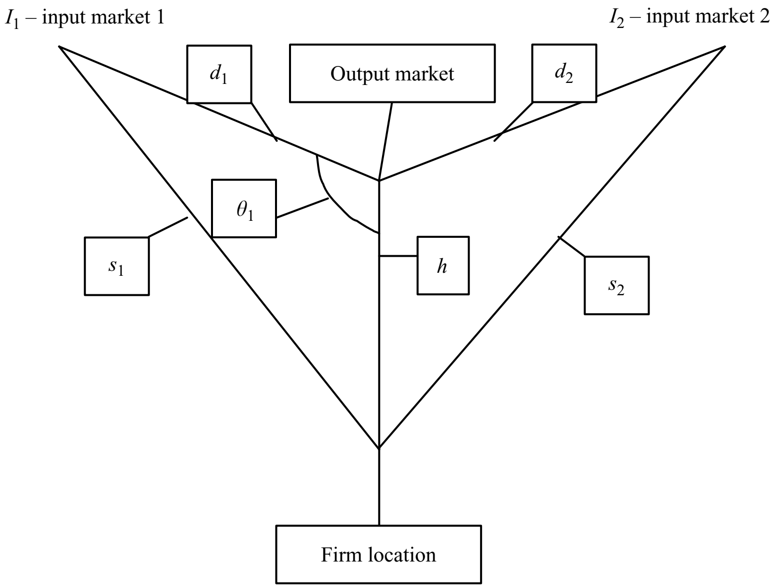

Figure 1. *The firm's location to the input and output markets*

location for the environment–development debate and trade–environment debate. The results show that uncertainty about environmental regulations in the form of the abatement investment and taxes leads a risk-averse firm to locate closer to the output market. Under uncertainty, an increase in input and/or emission taxes leads to a decrease in the distance between a risk-averse firm's location and the output market, while it does not impact a risk-neutral firm's location decision. The results have implications for the design and implementations of environmental policies for pollution control, public policies for regional development, international trade, and environment–development debate.

2. The model

We consider a competitive firm employing two transportable inputs, x_1 and x_2, to produce output Y. The inputs are available at the input markets I_1 and I_2. The firm supplies output to a consumption center (output market). Let d_i be the distance between the output market and the input markets and h be the distance between the output market and the firm's location (figure 1). Using the law of cosines, the distance from the firm's location to the input markets is expressed as: $s_1 = \sqrt{d_1^2 + h^2 - 2d_1 h \cos\theta_1}$ and $s_2 = \sqrt{d_2^2 + h^2 - 2d_2 h \cos|\theta_2 - \theta_1|}$, where θ_1 is the angle of d_1 and h, and θ_2 is the angle of d_1 and d_2. Once h and θ_1 are fixed, the location of the firm is fully determined, as the distance between input and output markets is known. The shipment cost of output and inputs per unit distance is r_i, $i = 0, 1, 2$ for output and two inputs, respectively.

We consider environmental regulations in the form of mandatory technology adoption. With environmental regulation, firms are usually required to use less pollution generating technologies, which requires capital investment in new technologies. We also consider the impacts of various market-based policies such as input, output and emission taxes on the firm's location decision, which can be used to regulate the industry through influencing the firm location decision and affecting optimal input use and output.

The firm is assumed to face two types of uncertainty in choosing the plant location: technology (production) and environmental policy. The production technology is represented by the following stochastic production function, $Y = F(x_1, x_2, \varepsilon)$, where ε is a random variable with mean zero representing the effects of variations in stochastic weather conditions, labor efficiency, etc. This function is assumed to be a twice continuously differentiable function with $F_{x_i} > 0$ and $F_{xx_i} < 0$, $i = 1, 2$ for all values of ε. It is assumed that the higher values of ε represent the more favorable state of nature because increased ε enhances the production, i.e. $F_\varepsilon > 0$. Input prices (w_1 and w_2) and output price (P) are assumed to be known with certainty.[3] Pollution (waste) generated, z_i, is represented as a function of input use as: $z_i = z_i(x_i)$.

The firm makes decisions concerning plant location and input combinations under uncertainty about the cost of the environmental regulation. Assume that the cost of abatement depends on where the firm locates its operation and the volume of pollution generated ($K(h, \theta_1, z_1(x_1), z_2(x_2))$). The cost of environmental regulation could vary spatially because of variations in stringency of environmental regulations across states or countries as in the case of air and water pollution in the United States. Additionally, in many cities, zoning has been used to control the use of land and improve environmental quality by identifying areas around cities that require relatively high costs of abatement investment compared with the other areas. We take into account the stringency of the environmental regulation across space by making the cost function depend on h and θ_1. Since the extent of the environmental regulation varies across space with h and θ_1, the cost of abatement investment could take the form of $K(h, \theta_1, z_1(x_1), z_2(x_2)) = \alpha C(h, \theta_1, z_1, z_2)$, where α is an uncertain parameter with mean $\bar{\alpha}$ and with the support $[0, \alpha^U]$. Uncertainty about the costs of the imposition of environmental regulations or liabilities is represented by assuming that α is a stochastic shift variable in the cost function.

The non-stochastic part of the cost function $C(h, \theta_1, z_1, z_2)$ is an increasing function of pollution generated, i.e. $C_z > 0$ and $C_{zz} > 0$. The sign of C_h determines whether the stringency of environmental regulation and therefore the cost of regulation increases or decreases as the firm moves closer to the output market. If $C_h < 0$, the closer the firm is located to the output market the higher the extent of regulation. In an international

[3] In this paper, we consider a competitive firm's location decision. Strategic reasons for relocation may also be important for firms that operate in a monopoly or oligopoly environment, where firms' output and input use would affect output and input prices.

context, the output market would be considered as a developed country with high environmental regulation. As the firm moves its operation from a developed country to a developing country, the cost of regulation is expected to decrease. The cost of regulation could also be uniform across space but vary with the pollution generated, i.e. $K(h, \theta_1, z_1, z_2) = \alpha C(z_1, z_2)$ and $C_h = 0$. In this type of regulation, given the same level of pollution generated, firms have to meet the same standards regardless of their locations. We examine the implications of alternative cost functions for the optimal location of the firm.

The firm is assumed to have a von Neuman–Morgenstern utility function, *U(W)* defined on wealth W with $U_W > 0$ and $U_{WW} < 0$. The wealth is represented by sum of the initial wealth, W_0, and returns from production, π. The Arrow–Pratt measure of absolute risk aversion at the expected post-risk wealth ($\bar{W}$) is defined as $R_A = -\frac{U_{WW}(\bar{W})}{U_{WW}(\bar{W})}$ (Arrow, 1971). Note that relative risk aversion is $R_R = R_A\bar{W}$.[4] The firm's objective is to maximize the expected utility of the wealth to find the optimal input combinations and its location. The firm's profit is given by

$$\pi = (P - r_o h)Y - \sum_{i=1}^{2}(w_i + r_i s_i)x_i - K(h, \theta_1, z_1(x_1), z_2, (x_2)) \tag{1}$$

Firm location decision under uncertainty

The firm maximizes the expected utility of wealth to find the optimal plant location and input combinations as

$$\max_{x_1, x_2, h, \theta_1} E[U(W_0 + \pi)] \tag{2}$$

We use a three-stage algorithm to solve the firm's decision problem. The first stage of the optimization problem involves finding the optimum amount of x_i that maximizes the expected utility at a given location (h, θ_1). The first-order conditions for first-stage maximization are

$$\frac{\partial E[U]}{\partial x_i} = E\left[U_W((P - r_o h)F_i - (w_i + r_i s_i) - \alpha C_{z_i}\partial z_i/\partial x_i)\right] = 0 \quad i = 1, 2 \tag{3}$$

The second-order conditions for the maximum are assumed to be met, that is $\partial^2 E[U]/\partial x_i^2 < 0$ and $\partial^2 E[U]/\partial x_1^2 - \partial^2 E[U]/\partial x_2^2 - (\partial^2 E[U]/(\partial x_1 \partial x_2))^2 > 0$. Under production uncertainty only, equation (3) can be re-written as

$$E\left[(P - r_o h)F_i - (w_i + r_i s_i) - \bar{\alpha} C_{z_i}\partial z_i/\partial x_i\right] + Cov(U_w, F_i)/E[U_w] = 0 \qquad i = 1, 2 \tag{4}$$

[4] There are good theoretical and empirical reasons to assume that absolute risk aversion is decreasing and relative risk aversion is increasing in wealth (i.e., $dR_A/dW < 0$ and $dR_R/dW > 0$). A number of empirical studies have found the evidence supporting this assumption (Bar-Shira *et al.*, 1997; Isik and Khanna, 2003).

where the covariance $Cov(U_W, F_i)$ is positive (negative) when $F_{i\varepsilon} > (<)0$. Thereby, x_i is a risk-increasing (risk-decreasing) input when $F_{i\varepsilon} > (<)0$ under technology (production) uncertainty.

Let $x_i^*(h, \theta_1)$ be the values of x_i satisfying equation (4) and let $Y^*(h, \theta_1)$ and $\pi^*(h, \theta_1)$ be the corresponding values. The second stage of the optimization problem is to find the location variable θ_1 that maximizes $E[U(W_0 + \pi^*)]$ for a given h. Note that the firm only needs to find the optimal location variable θ_1 because θ_2 is known with the two input markets. The first-order condition for an interior θ_1 is given by

$$\frac{\partial E[U(W_0 + \pi^*)]}{\partial \theta_1} = E\left[U_W\left(-\sum_{i=1}^{2} r_i s_{i\theta_1} x_i^* - \alpha C_\theta\right)\right] = 0 \tag{5}$$

Finally, the third stage of the optimization problem is to find an optimum h that maximizes $E[U(W_0 + \pi^*(h, \theta_1^*(h)))]$, where $\theta_1^*(h)$ denotes the value of θ_1 satisfying (5). By differentiating $E[U(W_0 + \pi^*(h, \theta_1^*(h)))]$ with respect to h, the first-order condition for an interior h is[5]

$$\frac{\partial E[U(W_0 + \pi^*)]}{\partial h} = E[U_W \pi_h] = 0 \tag{6}$$

where $\pi_h = (-r_0 Y^* - \sum_{i=1}^{2} r_i s_{ih} x_i^* - \alpha C_h)$.

Impacts of environmental regulation on location decisions under production uncertainty

We now examine the impacts of environmental regulation on the firm's location decision under production uncertainty, assuming that there is no uncertainty about the environmental regulation.

Proposition 1

Under production uncertainty, an increase in the cost of the environmental regulation will move a risk-averse firm away from the output market, if the cost of the regulation decreases as the firm moves away from the output market. However, imposition of the uniform cost of the environmental regulation does not affect the firm's location decision.

Proof

Assume that there is no uncertainty about environmental regulation or uncertainty about implementation of the regulation and therefore $K(h, \theta_1) = \bar{\alpha} C(h, \theta_1, z_1, z_2)$. The first-order condition in (6) becomes $E[U_W \pi_h] = 0$, where $\pi_h = (-r_0 Y^* - \sum_{i=1}^{2} r_i s_{ih} x_i^* - \bar{\alpha} C_h) = 0$. The impact of a marginal increase in the cost of the environmental regulation through an increase in $\bar{\alpha}$ on the firm location is examined by totally differentiating (6)

[5] The second-order condition ($E[U_W \pi_{hh}] + E[U_{WW}(\pi_h)^2] < 0$) is assumed to be met. Given that $s_{hh} < 0$, it holds if $C_{hh} > 0$ and $\pi_{hh} < 0$ (i.e., $\pi_{hh} = -\sum_{i=1}^{2} r_i s_{ihh} x_i^* - \alpha C_{hh} < 0$). If $C_{hh} \leq 0$ and therefore $\pi_{hh} > 0$, then it is satisfied when $E[U_W \pi_{hh}] < -E[U_{WW}(\pi_h)^2]$.

to obtain:

$$\frac{\partial h}{\partial \bar{\alpha}} = -\frac{1}{H} E[U_{WW}(\pi_h \pi_{\bar{\alpha}}) + U_W \pi_{h\bar{\alpha}}] = \frac{C_h}{H} E[U_W] \tag{7}$$

where $H < 0$ is the second-order derivative of the third-stage maximization problem. The sign of (7) is determined by C_h. An increase in the cost of the environmental regulation decreases the distance between the firm's location and the output market, if the cost of the regulation increases as the firm moves away from the output market ($C_h > 0$). On the other hand, if the cost of the regulation decreases with h ($C_h < 0$), then an augmented regulation cost increases the distance between the firm's location and the output market. If a developed country such as the United States or European Union represents the output market, increased environmental regulation causes the firm to locate in a developing country with less stringent regulation.

Assuming that the cost of the environmental regulation (i.e., stringency of the environmental regulation) is uniform across space (i.e., $K(h, \theta_l) = \bar{\alpha} C(z_1, z_2)$ and $C_h = 0$), $\frac{\partial h}{\partial \bar{\alpha}} = 0$, then an increase in the cost of the environmental regulation does not have any impact on the firm's location. These results indicate that an increase in the stringency of harmonized environmental regulations does not have any effect on the location of individual firms.

Impacts of environmental regulation uncertainty on firm location decisions
We now analyze the impacts of an increase in uncertainty about the cost of the environmental regulation on the firm's location decision under uncertainty about production and environmental regulations.

Proposition 2
An increase in uncertainty about environmental regulation (the cost of abatement investment) leads a risk-averse firm to locate closer to the output market, if the cost of regulation is uniform across space or the cost of the regulation increases as the firm moves away from the output market.

Proof
We define the marginal increase in uncertainty about the cost of the abatement investment as the multiplicative mean-preserving spread of the probability distribution of α. Let $\alpha^* = \gamma(\alpha - \bar{\alpha}) + \bar{\alpha}$. An increase in γ represents a mean-preserving spread of the original distribution of α (Rothschild and Stiglitz, 1970). Totally differentiating the first-order condition in (6) leads to

$$\begin{aligned}\frac{\partial h}{\partial \gamma} &= -\frac{1}{H} E[U_{WW}(\pi_h \pi_\gamma) + U_W \pi_{h\gamma}] \\ &= -\frac{1}{H\gamma} E[U_{WW} \pi_h (\pi - E[\pi]) + U_W (\pi - E[\pi]) C_h / C] \end{aligned} \tag{8}$$

where $\pi_\gamma = (\pi - E[\pi])$ and $\pi_{h\gamma} = (\pi - E[\pi]) C_h / C$ given that Y^* is fixed at its optimum quantity. To determine the sign of equation (8), we follow an approach used by Diamond and Stiglitz (1974) and Sandmo

(1971). As shown in the appendix, if absolute risk aversion is decreasing, then $E[U_W(\pi - E\pi)] < 0$ and $E[U_{WW}\pi_h] > 0$, and if relative risk aversion is increasing, then $E[U_{WW}\pi\pi_h] < 0$. Thus, equation (8) is negative if $C_h > 0$, indicating that an increase in uncertainty about the environmental regulation leads the firm to locate closer to the output market. When $C_h < 0$, equation (8) is positive if $E[R_A e_h^{\pi}\pi] < e_h^C$. In this case, the impact of regulation uncertainty depends on the degree of risk aversion and the elasticities of cost (e_h^C) and profit (e_h^{π}). On the other hand, if the cost of the regulation is uniform across space ($C_h = 0$), the risk-averse firm is likely to move closer to the output market. These results indicate that, if the output market were based in a developed country such as the United States and the cost of the regulation is uniform, uncertainty about environmental regulation would cause the risk-averse firm to locate nearer to the developed country.

There are two opposing effects of an increase in the uncertainty about environmental regulation on the firm's location. First, increased uncertainty makes a risk-averse firm worse off. Because the variance of the profits $\gamma^2 C^2 Var(\alpha)$ is positively related to h, a risk-averse firm tends to locate closer to the output market in order to reduce its exposure to uncertainty. Second, a lower output decreases the risk to the more risk-averse firm, *ceteris paribus*. Thus, the more risk-averse firm may choose to produce in a more risky site by locating farther away from the output market. Under decreasing absolute risk aversion and increasing relative risk aversion, the first effect dominates the second effect (Briys and Eeckhoudt, 1985), leading a risk-averse firm to locate closer to the output market under uncertainty than under certainty.

Under risk neutrality, the firm maximizes the expected profits and therefore $\frac{\partial h}{\partial \gamma} = -\frac{1}{H}E[\pi_{h\gamma}]$, which is equal to zero regardless of whether the regulation is uniform or not. Thus, uncertainty about the environmental regulation does not have any impact on a risk-neutral firm's location decision. These results indicate how risk aversion changes the impacts of uncertainty on the firm's location decision.

Proposition 3

Under uncertainty about production and environmental regulation, a more risk-averse firm will locate nearer to the output market.

Proof

Assuming that preferences of the firm can be represented by a utility function of the form $U(W_0, \pi; \eta)$, we examine the locational effect of risk aversion as in Diamond and Stiglitz (1974). The index η is positively related to the absolute risk-aversion function ($\partial R_A/\partial \eta > 0$). Totally differentiating the first-order condition in (6), we obtain

$$\frac{\partial h}{\partial \eta} = -\frac{1}{H}E[U_{WW}\pi_h(\partial U/\partial \eta)] \qquad (9)$$

With $\partial U/\partial \eta < 0$, equation (9) is negative if absolute risk aversion is decreasing ($E[U_{WW}\pi_h] > 0$). This indicates that the more risk averse the firm is, the lower the distance between the output market and the location of the firm. Under uncertainty about environmental regulations, the firm moves closer to the output market in order to reduce the variability of returns. As the degree of risk aversion rises, the variance of the profit increases. The risk-averse firm with non-increasing absolute risk aversion is likely to seek to reduce the variability of return or to cut its exposure to uncertainty by locating closer to the output market.

Impacts of output, input and emission taxes on location decision

We now examine the impacts of various market-based policies such as output, input, and emission taxes on a risk-averse firm's location decision under production and environmental policy uncertainty.[6] Market-based instruments such as taxes or subsidies are typically proposed as a means of implementing environmental policies. For example, taxes on observable factors such as input use have been proposed for achieving desirable reductions in runoff of fertilizers and have been used in the United States and Europe (Larson *et al.*, 1996). Now, assume that the industry is regulated by imposing taxes on output, input, or emission. The profit of the firm with a pre-determined output tax is given by $\pi = (P - r_o h)(1 - t_0)Y - \sum_{i=1}^{2}(w_i + r_i s_i)x_i$.

Proposition 4

Under production uncertainty, an augmented output tax could increase or decrease the distance between the output market and the firm's location. An increase in the uncertainty about the output tax leads a risk-averse firm to locate closer to the output market.

Proof

The first-order condition of the firm's location decision is similar to (6), with the only difference being the definition of wealth and $\pi_h = (-r_0 Y^*(1 - t_0) - \sum_{i=1}^{2} r_i s_{ih} x_i^*)$. We totally differentiate the first-order condition to obtain:

$$\frac{\partial h}{\partial t_0} = -\frac{1}{H} E[-U_{WW}(\pi_h (P - r_o h)Y^*) + U_W r_0 Y^*] \qquad (10a)$$

The sign of equation (10a) is determined by the signs of the terms inside the brackets. If $E[R_A \pi_h (P - r_o h)] < r_0$, then (10a) is negative, indicating that the distance between the output market and the site of firm's location decreases with increased output tax. Under risk neutrality, increased output tax increases the distance between the output market and the firm's location. If the output market is based in a developed country, an increased output tax in that country encourages a risk-neutral firm to locate in a developing country with less stringent regulation.

[6] In this section, we only consider the impacts of market-based policies on the firm's location decision. However, it is possible that some combinations of these policies along with the abatement investment could be implemented to address certain environmental problems.

We now consider the impact of an increase in uncertainty about the output tax on the firm's location decision. Let $t_0^* = \gamma(t_0 - \bar{t}_0) + \bar{t}_0$, where γ represents a mean-preserving spread of the original distribution of t_0 (Rothschild and Stiglitz, 1970). Totally differentiating the first-order condition in (6) with the output tax results in

$$\frac{\partial h}{\partial \gamma} = -\frac{1}{H\gamma} E\left[U_{WW}\pi_h(\pi - E[\pi]) - U_W\left(\frac{r_o(\pi - E[\pi])}{(P - r_o h)}\right)\right] \tag{10b}$$

The sign of equation (10b) is indeterminate and depends on the signs of the terms inside the brackets. Given that $[R_A\pi_h(\pi - E[\pi])] < -[\frac{r_o(\pi - E[\pi])}{(P - r_o h)}]$, (10b) will be negative, indicating that the distance between the output market and the firm's location decreases with increased output tax uncertainty. With a risk-neutral firm, equation (10b) is equal to zero, indicating that uncertainty about environmental regulation does not affect the firm's location decision.

Proposition 5

Under uncertainty, an increase in an input tax and/or an increase in uncertainty about its implementation decreases the distance between a risk-averse firm's location and the output market. An increased input tax does not impact a risk-neutral firm's location decision.

Proof

Under an input tax policy, the firm's input cost (w_i) in equation (1) will be replaced by $w_t(1 + t_x)$. The first-order condition of the firm's location decision is similar to (6), with the only difference being the definition of wealth and $\pi_h = (-r_0 Y^* - \sum_{i=1}^{2} r_i s_{ih} x_i^*)$. Totally differentiating the first-order condition leads to

$$\frac{\partial h}{\partial t_x} = \frac{1}{H} E\left[U_{WW}\pi_h\left(w_i x_i^*\right)\right] \tag{11a}$$

Equation (11a) is negative if absolute risk aversion is decreasing. Hence, an increase in the input tax results in a decrease in the distance between the output market and the firm's location, causing firms to concentrate around the output market, which is more likely to be populated. In an international perspective, these results imply that, if the output market were in a developed country, increased input tax in that country would cause the firm to stay closer to the developed country. Under risk neutrality where the firm maximizes the expected profits, an increase in the input tax, however, does not have any impact on a risk- neutral firm's location.

We also analyze the marginal impact of an increase in uncertainty about the input tax on the firm's location decision by letting $t_x^* = \gamma(t_x - \bar{t}_x) + \bar{t}_x$, as in the case of examining the impacts of uncertainty about output taxes. Totally differentiating (6) with the input tax leads to:

$$\frac{\partial h}{\partial \gamma} = -\frac{1}{H} E[U_{WW}\pi_h(\pi - E[\pi])] \tag{11b}$$

Equation (11b) is negative and indicates that an increase in uncertainty about the input tax leads the firm to locate closer to the output market if absolute risk aversion is decreasing. In our model, if the output market described a developed country, increased uncertainty about the environmental regulation would lead a risk-averse firm to locate closer to a developed country.

Proposition 6
An increase in an emission tax and/or uncertainty about its implementation decreases the distance between a risk-averse firm's location and the output market. Uncertainty about emission taxes does not impact a risk-neutral firm's location decision.

Proof
Given that $z_i = z_i(x_i)$, the profit of the firm with the emission tax is given by $\pi = (P - r_o h)Y - \sum_{i=1}^{2}(w_i + r_i s_i)x_i - \sum_{i=1}^{2} t_{ei} z_i(x_i)$. The first-order condition with respect to h is similar to (6), with the only difference being the definition of wealth and $\pi_h = (-r_0 Y^* - \sum_{i=1}^{2} r_i s_{ih} x_i^*)$. Totally differentiating the first-order condition with the emission tax leads to

$$\frac{\partial h}{\partial t_{ei}} = \frac{1}{H\gamma} E[U_{WW}\pi_h z_i(x_i)] \tag{12a}$$

Equation (12a) is negative if absolute risk aversion is decreasing. Hence, an increase in the emission tax decreases the distance between the output market and the firm's location, causing firms to concentrate around the output market. If the output market were considered as a developed country, an increase in the emission tax would lead a risk-averse firm to locate nearer to the developed country. Note that an increase in the emission tax does not have any impact on a risk-neutral firm's location.

Now suppose that the pollution generated is a function of x_i, h, and θ_1 as: $z_i = z_i(h, \theta_1, x_i)$. In this case, the pollution generated varies across space, given the same level of input use. For example, this would be the case in agriculture, where the runoff generated depends not only on the input use but also on the physical soil characteristics, weather conditions, and production technology available to the firm across space. With the assumption of $z_i(h, \theta_1, x_i)$ and risk aversion, $\pi_h = (-r_0 Y^* - \sum_{i=1}^{2} r_i s_{ih} x_i^* - z_{ih})$ and $\frac{\partial h}{\partial t_{ei}} = \frac{1}{H} E[U_{WW}\pi_h z_i(x_i, \theta_1, x_i) + U_W z_{ih}]$. If $z_{ih} > 0$, then $\partial h/\partial t_{ei} < 0$. If $z_{ih} < 0$, then $\partial h/\partial t_{ei} > 0$, provided that $E[R_A \pi_h z_i] > z_{ih}$. On the other hand, under risk neutrality, $\partial h/\partial t_{ei} < (>)0$, if $z_{ih} > (<)0$. Thus, an increased emission tax does not impact a risk-neutral firm's location if the environmental regulation is uniform across space, while it is likely to affect the location choice if the pollution function depends on h.

We also analyze the marginal impact of an increase in uncertainty about emission taxes on the firm's location decision. Let $t_{ei}^* = \gamma(t_{ei} - \bar{t}_{ei}) + \bar{t}_{ei}$, as in the case of output and input taxes analyzed above. Totally differentiating (6) with the emission tax and $z_i = z_i(h, \theta_1, x_i)$ leads to

$$\frac{\partial h}{\partial \gamma} = -\frac{1}{H\gamma} E[U_{WW}\pi_h(\pi - E[\pi]) + U_W(\pi - E[\pi])z_{ih}] \tag{12b}$$

As shown above, under non-increasing absolute risk aversion and non-decreasing relative risk aversion, equation (12b) is negative if $z_{ih} \geq 0$. This indicates that augmented uncertainty about environmental regulation leads the firm to locate closer to the output market. This occurs because a risk-averse firm seeks to reduce its exposure to uncertainty. If $z_{ih} < 0$, then the impact of uncertainty on the location decision is ambiguous. If $z_i = z_i(x_i)$ (i.e., $z_{ih} = 0$), an increase in uncertainty about the emission taxes leads the risk-averse firm to locate closer to the output market. Under risk neutrality, the firm maximizes the expected profits and therefore $\frac{\partial h}{\partial \gamma} = -\frac{1}{H} E[\pi_{h\gamma}]$, which is equal to zero regardless of whether z_{ih} is zero or not.

3. Implications of firm location for environmental change and economic development

The analytical results from this paper have important implications for the design and implementation of environmental policies, the trade–environment debate, and the environment–development debate because firm location is central to the understanding of these crucial issues. The potential for conflicts between environmental concerns and international trade has been increasing. The past two decades have seen a proliferation of national environmental laws and international environmental agreements along with a rapid expansion of international trade. Environmental law increasingly dictates how countries should structure their economies, and trade law increasingly defines how countries should structure their domestic laws and policies in environmental protection (Nordstrom and Vaughan, 1999; Dean, 2002). Thus, trade liberalization can have significant impacts on the environment. Firms may transfer cleaner technologies abroad when a trade agreement results in a more open market (Bandara and Coxhead, 1999). Trade liberalization may also promote the spread and use of less-environmentally friendly technologies in developing countries (Wheeler, 2001).

Location decisions of individual firms have an international context, with concerns about companies shifting investment outside developed countries such as the United States and European Union (Rauscher, 1995). For example, the European Union experience with its Nitrate Directive demonstrates that limiting producers' options with strict regulation of nitrate levels in an area with a limited land base has the potential to reduce the scale and to influence the location of animal production. Additionally, harmonization of environmental standards across international boundaries is a contentious topic in World Trade Organization discussions, because of possible effects on the location of businesses and geographic dispersion of emissions. If uniform environmental regulations were to raise costs of production in some countries so high that they could no longer be competitive in export markets, producers in those countries would likely appeal for an exemption, and some countries might be willing to enhance their export competitiveness at the expense of the environment. As the analytical results of this paper indicate, in some cases firms in developed countries with high environmental regulations would prefer to move their operations to developing countries with less stringent regulations.

The possibility of individual firms relocating in response to environmental costs has been a major concern for public policy and economic development (Markusen *et al.*, 1995; Motta and Thisse, 1994). Environmental costs are an important factor in a firm's location decision, and have been the subject of widespread debate. In developed countries, a key concern of the environmental community is the prospect of a 'race to the bottom', where developing countries try to lure investment by lowering or not enforcing their environmental standards. This is the pollution haven argument – that under free trade, firms will migrate to places where environmental regulations are less stringent. Developing countries have weaker environmental regulations because of income and political economy considerations. There seems to be a well-documented relative growth of pollution-intensive industries in developing countries. More stringent environmental regulations can impose additional economic costs by distorting the spatial pattern of economic development – inducing some regions and countries to be at a competitive disadvantage when vying for new plants. Some recent studies suggest that regions and countries with relatively stringent environmental regulations attract fewer domestic plants and that tougher environmental standards in richer countries force polluting industries to relocate in developing nations with weaker regulations (Jeppessen *et al.*, 2002; Mani and Wheeler, 1999). Additionally, the threat of relocation by firms may create a climate where government regulators balk at strengthening their environmental laws for fear of driving away existing business (UNCTAD, 1997). The results from this paper also have implications for policies that seek to harmonize state- or province-level environmental regulations in developed countries and regions such as the United States, the European Union, and Canada. For example, major changes have been implemented in federal water quality rules for the livestock industries in the United States, which would harmonize manure management standards across states.

The interrelationships between environmental regulations and industrial location behavior have come to be seen as essential features of regional development and have important implications for developing countries. Environmental law and regulation play an important role in shaping the attitudes and behavior of firms towards the environment (López, 2000). Many countries, including those in Central Europe and developing countries, have made increasing use of economic approaches. Market-oriented approaches can enhance capacity to deal with the issues of environment and development (Lee and Roland-Holst, 1997). The results from this study have implications for appropriate efforts to explore and make more effective use of economic approaches in economic development policies, and to understand the relationship between the environment and development. For example, if the output market in our theoretical model is based in developed countries such as the United States or the European Union, environmental costs will decrease if the firm is located at some distance from the United States or the European Union as less developed countries are expected to have less stringent environmental policies. These results would provide an alternative explanation of increasing relocation and outsourcing of individual firms from developed countries to developing countries.

Some trade–environmental conflicts also reflect the sharp differences between developed and developing countries over trade and environmental policy. Several developing countries may be reluctant to take the lead in raising their environmental standards for fear of jeopardizing their comparative advantage. Although there is growing recognition in developing nations that environmental and development objectives must become more compatible, they do not have the resources to act on their environmental problems, given more immediate problems like poverty and debt. As developed countries reassess their trade positions with respect to developing countries, environmental issues will increasingly enter into the debate. Future trade agreements will likely include imposing higher environmental standards for developing countries. As the results of this study reveal, requiring higher environmental standards would affect the location of various industries and individual firms in developing countries.

The results also have implications for the design and implementation of spatial environmental policies for pollution control. It has generally been seen that businesses prefer setting up their production facilities near big cities because this gives them proximity to the consumer market. There has been a large increase in industrial development around the major cities. Emissions from these industries are of concern to neighboring residents in many locations. Many cities have used zoning to improve the environmental quality. The results obtained in this paper illustrate the usefulness of spatial environmental policies that aim at encouraging firms not to locate nearer to the output markets and the importance of reducing uncertainty about environmental regulations in implementing these policies.

4. Conclusions

This paper develops a theoretical model of firm decision making to examine the impacts of environmental regulations on a competitive firm's production and location decisions under uncertainty about production and environmental regulation. It also provides a systematic analysis of a risk-averse firm's choice of plant location and its response to taxes such as input, output, and emission when deciding its location under uncertainty. This paper contributes to the literature by obtaining comparative statics results with respect to the level of environmental regulation uncertainty, and by deriving results regarding the spatial effects of environmental regulations on the firm location decision. It also examines the implications of results for trade–environment debate, environment–development debate, and international environmental policies.

The comparative statics results show that an augmented cost of the environmental regulation does not impact a risk-neutral firm's location decision, if the cost of the regulation is uniform across space. Increased emission taxes or input taxes cause the risk-averse firm to locate closer to the output market. Uncertainty about environmental policies (cost of the abatement, output taxes, emission taxes, and input taxes) has the potential to affect the optimal location of the firm. In particular, it leads a risk-averse firm to move closer to the output market that is likely to be more populated. Thus, under policy uncertainty, environmental policies may not be effective in encouraging firms not to locate nearer to the output markets or consumption centers.

The results from this paper provide insight for evaluating the influence of market-based policies on regional and economic development. Tax policies and risk-reducing policies have impacts on regional development and on the environment through affecting the firm location decision. The results emphasize the importance of environmental regulations for the firm location decision and have implications for understanding the debate on environment and development as well as the relationship between development and environmental change. The results also have implications for the design and implementation of spatial environmental policies for pollution control.

The relationship between environmental regulations and firm location has become an important characteristic of economic development for developing countries. Firm location is central to the environmental policy design, economic development, trade–environment debate, and environment–development debate. The results from this paper have important policy implications for the environment–development debate and environmental change. Understanding firm location is important to evaluate the potential conflicts between environmental concerns and international trade and to formulate public policies affecting the economic development and environmental change. Increasing concerns about companies shifting investment outside developed countries have made location decisions of individual firms an important international policy issue. Environmental costs are considered to be a crucial factor in a firm's location. Harmonization of environmental standards across countries can have significant effects on the location of businesses and geographic dispersion of emissions. Increased environmental regulations of developing countries would induce these countries to be at a competitive disadvantage. Because the interrelationships between environmental regulations and firm location are essential features of regional development, environmental regulation can play an important role in determining the future development of many regions and developing countries.

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Appendix

Consider two utility functions, U and W. The utility function W represents greater risk aversion than U if there exists an increasing and strictly concave function k such that $W = k(U)$. The first-order condition for an interior h for the utility function W requires

$$E[k'(U)U'\pi_h] = 0. \tag{A1}$$

Let $\hat{\alpha}$ be the value of α such that $\pi_h = (-r_0 Y^* - \sum_{i=1}^{2} r_i s_{ih} x_i^* - \hat{\alpha} C_h) = 0$. Based on the definition that $R_A = -U_{WW}/U_W$, a decreasing R_A implies

$$-U_{WW}/U_W > (<) R_A(W_0 + \hat{\pi}) \quad \text{as}\, \alpha > (<) \hat{\alpha} \tag{A2}$$

For $\hat{\alpha} > \alpha$, because $\pi_h > 0$, the following occurs

$$U_{WW}(W_0 + \pi)\pi_h > -U_W(W_0 + \pi) R_A(W_0 + \hat{\pi})\pi_h \tag{A3}$$

The inequality in (A3) also holds for $\hat{\alpha} < \alpha$ because $\pi_h < 0$. Therefore

$$E[U_{WW}(W_0 + \pi)\pi_h] > -E[U_W(W_0 + \pi)\pi_h R_A(W_0 + \hat{\pi})] = 0 \tag{A4}$$

Equation (A4) indicates that $E[U_{WW}\pi] > 0$. Similarly, based on the definition of relative risk aversion such that $R_A = -(W_0 + \pi)U_{WW}/U_W$, an increasing R_R implies

$$-(W_0 + \pi)U_{WW}/U_W < (>) R_R(W_0 + \hat{\pi}) \quad \text{as}\, \alpha > (<) \hat{\alpha} \tag{A5}$$

Using the same approach as above leads to $E[U_{WW}\pi\pi_h] < 0$. Therefore, if absolute risk aversion is decreasing, then $E[U_W(\pi - E\pi)] < 0$ and $E[U_{WW}\pi_h] > 0$, and if relative risk aversion is increasing, then $E[U_{WW}\pi\pi_h] < 0$.