Productivity Dispersion across Plants, Emission Abatement, and Environmental Policy

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Abstract

Empirical studies suggest systematic relationships between plant's productivity and plant's emissions and emission-abatement costs. This paper demonstrates that productivity dispersion across plants is an important factor that influences the transmission of environmental policy. Within a general equilibrium framework, I model heterogeneous polluting plants by allowing them to be differing in productivity and to choose optimally a discrete emission-reduction technology taking into account both the costs of reducing emissions and the competition in the goods market. An emission-reduction policy affects the distribution of plants with the advanced abatement technology and relocates resources and market shares across plants. As a result, the aggregate effects of an environmental policy depend on the degree of productivity dispersion. Using Canadian data, I show quantitatively that the aggregate effects of an environmental policy significantly affected by the degree of productivity dispersion both in the transition periods and in the long-run steady-state equilibrium.

Keywords: Heterogeneous plants, Abatement technology, Greenhouse Gas emissions
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1 Introduction

Empirical studies suggest systematic relationships between plant's productivity and plant's emissions and emission-abatement costs. This paper demonstrates that productivity dispersion across plants is an important factor that influences the transmission of environmental policy. Within a general equilibrium framework, I model heterogeneous polluting plants by allowing them to be differing in productivity and to choose optimally a discrete emission-reduction technology taking into account both the costs of reducing emissions and the competition in the goods market. An emission-reduction policy affects the distribution of plants with the advanced abatement technology and relocates resources and market shares across plants. As a result, the aggregate effects of an environmental policy depend on the degree of productivity dispersion. Using Canadian data, I show quantitatively that the aggregate effects of an environmental policy significantly affected by the degree of productivity dispersion both in the transition periods and in the long-run steady-state equilibrium.

Modelling the heterogeneity of polluting plants is motivated by the fact that plants' polluting and emission-reducing activities vary substantially across plants and exhibit systematic relationship with their levels of productivity. The Environmental Accounts and Statistics Division of Statistics Canada (2004, 2005) reported that there exists a large variation of abatement expenditures and choices of abatement technologies across plants both within an industry and across industries. There are also some empirical works that find some relationships between plants' productivity and their emission generation and reduction. For example, Shadbegian and Gray (2003) have found a negative relationship between emissions (weighted by output) and productivity levels; Gray and Shadbegian (1995) have found that a higher abatement spending is associated with a lower productivity level.

The existence of pronounced heterogeneity in polluting and emissions-reducing activities may cause the emission-reducing policies to generate substantial distributional effects. For example, an ad valorem emission tax leads to resource reallocation flowed from low productivity plants to high productivity plans. The positive effect of this relocation is that it increases the aggregate productivity. However, the emissions tax can also cause some low productivity plants to experience losses and to exit from the industry. This process may involve in wasting sunk costs in plants that exit and reducing varieties of goods that consumers could choose. The overall effects depend on which one is dominant.

Calibrated to match Canadian data, this paper shows that the aggregate cost of reducing 20%-25% of GHG emissions from the current level in Canadian industries, which is close to the target set in the Kyoto Protocol — 6% below the 1990 level, is about 2 times as large as that in a similar economy assumed without productivity dispersion. The higher costs are mainly due to the interaction between the productivity dispersion and the non-convex choice of new abatement technologies. In the economy with homogeneous plants, all the plants utilize more efficient abatement technologies, while in the economy with productivity dispersion, only 28% of plants adopt the new abatement technology. Hence, productivity dispersion divides plants into two groups with sharp difference in their efficiency of emission-reduction. The low productivity plants group has higher average abatement costs. This inefficient group is the source of the higher aggregate abatement costs.

The paper also studies the dynamics of an economy under emissions taxes. Taking advantage of the Ghironi and Melitz (2005) model, the current model with heterogeneous polluting plants is tractable not only in the steady state, but also in a dynamic setting. Considering the transition of the economy, it is still more costly to reduce emissions in the economy with productivity dispersion.

The rest of the paper proceeds as follows: Section 2 sets up the model and characterizes the equilibrium; Section 3 calibrates the model; Section 4 conducts numerical experiments; Section 5 concludes.

2 The Model

The economy is populated by a unit measure of identical households. The representative household is infinitely lived and has preferences over streams of consumption goods and pollutant stocks (pollution) at each date. The expected discounted life time utility is

$$\max_{\{m_t,q_t\}} E_0 \sum_{t=0}^{\infty} \beta^t [(1-\alpha) g(\frac{D_t}{\bar{D}}) m_t^{\rho} + \alpha {q_t}^{\rho}]^{\frac{1}{\rho}}. \tag{2.1}$$

Here, m_t is the consumption of clean goods, q_t is the consumption of an aggregate of dirty goods, and D_t is the level of the pollutant stock. The subjective discount factor is $\beta \in (0,1)$. Restrict $-1 < \rho < 0$, so that the clean goods and the dirty aggregate are poor substitutes. Let $\bar{D}$ be a threshold level of the pollutant stock, above which the pollution causes disutility. So $g(\frac{D_t}{\bar{D}}) = 1$ for all $D_t \leq \bar{D}$. If the pollutant stock is higher then the threshold value, $g(\frac{D_t}{\bar{D}}) = (\frac{D_t}{\bar{D}})^{\Psi}$, where $\Psi > 0$. The particular specification of g implies that the utility delivered by the clean goods is reduced as the pollution level increases and therefore the share of clean goods increases in the pollutant stock. [1].

Every household is endowed with l unit of resource per period. This resource is the only input required for production. The production of dirty goods generates emissions. The total amount of emissions generated in period t is denoted as E_t. Emissions accumulate according to

$$D_t = (1-\delta_1) D_{t-1} + E_t, \tag{2.2}$$

where $\delta_1 \in (0,1)$ is a decay factor for the pollutant stock. Let D_{-1} be the initial level of the pollutant stock.

Different dirty goods appear in the utility function through the following aggregator:

$$q_t = [\int_{i \in \Omega_t} {q_{i,t}}^{\frac{(\sigma-1)}{\sigma}} di]^{\frac{\sigma}{(\sigma-1)}} \tag{2.3}$$

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[1] The paper has also calculated the results using an alternative utility function in which the utility from goods and the disutility from pollution are separable. The results of this paper are not driven by the utility function specified here.

Here, $\sigma > 1$ is the elasticity of substitution across dirty goods, and Ω_t is the set of dirty goods available at period t. Let $\Omega = \cup_t \Omega_t$ be the entire set of dirty goods available over time, where Ω is assumed to be a continuum. Let $p_{i,t}$ denote the price of dirty goods $i \in \Omega_t$. The price of the aggregate of the dirty goods at t is

$$P_t = [\int_{i\in\Omega_t} {p_{i,t}}^{(1-\sigma)} di]^{\frac{1}{(1-\sigma)}}.$$

2.1 The Government

As specified, pollution is an externality that is unlikely to be internalized in a laissez-faire economy. This creates room for a government or institution to regulate pollution. In the model, the government is bestowed a role to monitor and control emissions on behalf of consumers. Two instruments are available: one is an ad valorem tax on emissions, the other is a uniform standard on emissions-output ratio. When the tax instrument is applied, the tax revenue is simply returned to consumers as a lump-sum transfer. The government's budget constraint is

$$T_t = \tau_t E_t, \tag{2.4}$$

where T_t is a lump-sum transfer to consumers, and τ_t is the tax rate.

2.2 The Producer's Problem

There are two sectors in this economy. One is a clean sector in which competitive plants produce goods without generating emissions. The other is a dirty sector which features monopolistic competition. That is, each plant monopolizes the production of one kind of differentiated goods $i \in \Omega$. Potential plants can choose to enter the clean sector freely or enter the dirty sector with a sunk entry cost $f_{e,t}$ in units of resource. The plants enter the dirty sector if the present value of the expected profit stream can cover this entry cost.

2.2.1 The Clean Sector

The clean goods M_t are produced by a linear production technology:

$$M_t = XL_{m,t},$$

where X represents the level of productivity and $L_{m,t}$ is the quantity of the resources used to produce goods M_t in period t. The competitive feature of this market ensures that the factor price equals the level of productivity, $w_t = X$. The supply of clean goods is determined by market clearing conditions.

2.2.2 The Dirty Sector

In the dirty sector, plants are monopolistically competitive. Under the specification of the aggregator in (2.3), each plant faces a constant elasticity σ. Hence, the optimal pricing strategy is to set the price as a constant markup, $\sigma/(\sigma-1)$, over the marginal cost.

Potential plants are identical before they enter the dirty sector. Upon entry, each plant draws a productivity level x from a common distribution $G(x)$ with support on $[x_{\min}, \infty)$. This productivity level remains constant for the plant thereafter. Thus, I can refer to a plant with productivity x as plant x.

In order to produce any, a plant needs to pay a fixed cost $f > 0$ in units of resource. For simplicity, I let all the plants share the same fixed cost over all the periods. Hence, some plants never produce if they draw a low level of productivity after entry. The production technology of a plant that draws productivity x is

$$q_t^s(x) = xL_{g,t}(x), \tag{2.5}$$

where $L_{g,t}(x)$ is the variable input required for producing goods x.

Producing the dirty goods generates air emissions. The amount of emissions generated by plant x is

$$e_t(x) = z_t(x)^{1-h} bL_{g,t}(x). \tag{2.6}$$

Here, $b > 0$ and $h \geq 1$ are constant. The variable $z_t(x)$ is the relative cleanness of producing goods x, which depends positively on the amount of resources that the plant puts into abatement. The above specification captures the intuitive idea that the amount of emissions increases with the amount of inputs in production and decreases with the inputs into abatement. For simplicity and tractability, I will assume that

$$z_t(x) = 1 + \frac{L_{a,t}(x)}{L_{g,t}(x)},$$

where $L_{a,t}(x)$ is the amount of resources that plant x puts into abatement. The total variable cost in plant x is $L_t(x) = L_{g,t}(x) + L_{a,t}(x)$.

When $z_t(x) = 1$, the parameter b captures the intensity of emissions generated from production. b is usually called the emission factor. New technologies can improve the emission factor b. I assume that a fixed investment is required to use the new abatement technology.

Note that the amounts of inputs into production and abatement are functions of the plant's productivity, x, as made explicit above. These inputs also depend on pollution regulation. Two types of regulation are studied: an ad valorem tax on emissions and a standard on the emission-output ratio. It will be shown that the level of productivity determines the amount of emissions and hence the scale effect of abatement technology. In turn, the abatement decision influences the costs and thus the price and sale.

An ad valorem Emission Tax The government monitors the polluting plants and imposes an ad valorem tax τ_t on emissions. Given the resource price w_t and the tax rate τ_t, the plant x chooses abatement technology and variable abatement input, and sets price according to a constant markup over variable cost. It is easy to show that this pricing strategy is optimal for the plant. The quantity of output is determined by equilibrium demand.

The plant chooses whether to invest in a new abatement technology, which requires a fixed investment $w_t f_{a,t}$ in every period and reduces b to b_n. To decide whether to choose the new technology, the plant compares the cost in each case. If the plant does not use the new abatement technology, the total variable cost is the sum of the variable costs used in production and abatement, plus the tax payment,

$$w_t(L_{a,t}(x) + L_{g,t}(x)) + \tau_t e_t(x).$$

The total variable cost can be rewritten as a function of the cleanness index $z_t(x)$:

$$z_t(x)w_tL_{g,t}(x) + \tau_t b z_t(x)^{1-h}L_{g,t}(x).$$

Given the production input $L_{g,t}$, the plant chooses the optimal cleanness index $z_t(x)$ to minimize the above cost. That gives

$$z_t = [\frac{\tau_t}{w_t}b(h-1)]^{\frac{1}{h}} \quad \text{if } \frac{\tau_t}{w_t}b(h-1) > 1,$$

and

$$z_t = 1 \qquad\qquad\qquad\qquad \text{otherwise.}$$

Note that this amount is identical for all plants who do not use the new technology.

If the plant chooses to use the new technology, the emission factor is reduced to $b_n(< b)$ and there is an additional fixed cost $w_tf_{a,t}$. The optimal choice of the cleanness index $z_t(x)$ in this case is

$$z_{n,t} = [\frac{\tau_t}{w_t}b_n(h-1)]^{\frac{1}{h}} \quad \text{if } \frac{\tau_t}{w_t}b_n(h-1) > 1,$$

and

$$z_{n,t} = 1 \qquad\qquad\qquad\qquad \text{otherwise.}$$

Note that, in both cases, if the tax rate is low such that $\frac{\tau_t}{w_t}(h-1) \leq \frac{1}{b}$ (or $\frac{1}{b_n}$), the plants find not worthwhile to incur variable abatement costs to reduce emissions.

A plant adopts the new abatement technology in period t if and only if the profit is higher after adopting it. Note that I have simplified the model by allowing for periodical choices of the new abatement technology. If the investment is not periodical, then the plant needs to compare the present value of the expected profit stream with the present value of the investment expenditures. However, in the steady state equilibrium, these two methods give identical results.

To compute the profit, I need the information about prices of the goods. The profit maximizing plants will set the prices according to a fixed markup over variable costs. That is

$$p_{1t}(x) = \varrho_n x^{-1}$$

and

$$p_{2t}(x) = \varrho x^{-1}.$$

ϱ_n and ϱ are defined as follows:

$$\begin{aligned} \varrho_n &= \frac{\sigma}{\sigma-1}\frac{w_t h}{h-1} z_{nt} && \text{if } z_{nt} > 1 \\ \varrho_n &= \frac{\sigma}{\sigma-1}(w_t + \tau_t b_n) && \text{otherwise} \end{aligned}$$

and

$$\begin{aligned} \varrho &= \frac{\sigma}{\sigma-1}\frac{w_t h}{h-1} z_t && \text{if } z_t > 1 \\ \varrho &= \frac{\sigma}{\sigma-1}(w_t + \tau_t b) && \text{otherwise} \end{aligned}$$

Using these formulas of prices, I can compute the levels of profit with and without the new abatement technology. Comparing the two, I find that a plant adopts the new abatement technology if and only if the plant's productivity is above a threshold level. This threshold is given as

$$x_{a,t} = \{\frac{w_t f_{a,t} \sigma}{P_t^\sigma Q_t[\ \varrho_n^{(1-\sigma)} - \varrho^{(1-\sigma)}]}\}^{\frac{1}{\sigma-1}},$$

where $Q_t = \{\int [q_t^s(x)]^{\frac{(\sigma-1)}{\sigma}} dx\}^{\frac{\sigma}{(\sigma-1)}}$, and the dirty aggregate supplied, Y_Q, equals NQ_t.

If $x \geq x_{a,t}$, the plant adopts the new abatement technology. I call such plants type I plants. The emission level of such a plant is

$$e_{1t}(x) = z_{n,t}^{1-h} b_n \varrho_n^{-\sigma} x^{\sigma-1} P_t^\sigma Q_t.$$

The profit of such a plant is

$$\pi_{1t}(x) = \frac{P_t^\sigma Q_t}{\sigma}[\frac{\varrho_n}{x}]^{1-\sigma} - w_t f_{a,t} - w_t f \quad .$$

If $x < x_{a,t}$, the plant does not use the new abatement technology. I call such plants type II plants. The emission level of such a plant is

$$e_{2t}(x) = z_t^{1-h} b \varrho^{-\sigma} x^{\sigma-1} P_t^\sigma Q_t.$$

The profit of such a plant is

$$\pi_{2t}(x) = \frac{P_t^{\sigma} Q_t}{\sigma} \; [\frac{\varrho}{x}]^{1-\sigma} - w_t f \quad .$$

A notable feature is that the elasticity of substitution among dirty goods, σ, influences the dispersion of emissions across plants. The higher is σ, the easier the goods can be substituted by others, and the larger is the dispersion of emissions.

Entry and Exit In every period, a plant can choose to produce the clean goods or to enter the dirty sector. If a plant chooses to enter the dirty sector at time t, a sunk entry cost $w_t f_{e,t}$ is incurred but the plant can start producing only at time $t+1$, which introduces a one-period time-to-build lag in the model. After entry, the plant draws a productivity level. As shown above, the plants' profit is an increasing function of the productivity level. Because every plant needs a positive fixed cost in order to produce, some low productivity plants do not produce and exit immediately after entry. The producing plants keep their productivity levels forever until an exogenous exit-inducing shock hitting on them with probability μ. This exit-inducing shock is independent of the plants' productivity levels, so $G(x)$, truncated at a threshold level, $x_{e,t}$, above which plants produce, also represents the productivity distribution of all producing plants.[2]

Plant Averages According to the above analysis, the mass of producing plants that use the new abatement technology in period t is $N_{1,t} = [1 - G(x_{a,t})]\, N_t$, and the mass of producing plants that do not adopt the new abatement technology in period t is $N_{2,t} = [G(x_{a,t}) - G(x_{e,t})]\, N_t$. Following Melitz (2003), I assume that productivity x obeys Pareto distribution with a lower bound $x_{\min}$ and shape parameter $k > \sigma - 1$. That is $G(x) = 1 - (x_{\min}/x)^k$, where k governs the dispersion of productivity. As k increases, productivity dispersion decreases, and the levels of plants' productivity become increasingly concentrated toward their lower bound $x_{\min}$. To see

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[2] In order to simplify the analysis, I will look at only stationary equilibria, in which the tax rate or the standard is identical in every period. A change in pollution regulation can be seen as a permanent shock, which can move one stationary equilibrium to another.

this, note that the mean of x is $\frac{k}{k-1}x_{\min}$ and the variance of x is $\frac{k}{k-2}x_{\min}^2$. Fixing the mean, say at $\bar{x}$, the variance is $\frac{(k-1)^2}{k(k-2)}\bar{x}$, which decreases in k for all $k > 2$.

Define two special "average" productivity levels, an average $\tilde{x}_{1,t}$ for all producing type I plants, and an average $\tilde{x}_{2,t}$ for all producing type II plants:

$$\tilde{x}_{1,t} = \left[\frac{1}{1-G(x_{a,t})}\int_{x_{a,t}}^{\infty} x^{\sigma-1} dG(x)\right]^{\frac{1}{\sigma-1}} = \upsilon x_{a,t},$$

and

$$\tilde{x}_{2,t} = \left[\frac{1}{G(x_{a,t})-G(x_{e,t})}\int_{x_{e,t}}^{x_{a,t}} x^{\sigma-1} dG(x)\right]^{\frac{1}{\sigma-1}} = \upsilon x_{e,t}\left[\frac{1-\vartheta^{k+1-\sigma}}{1-\vartheta^{k}}\right]^{\frac{1}{\sigma-1}},$$

where $\upsilon = (\frac{k}{k+1-\sigma})^{\frac{1}{\sigma-1}}$ and $\vartheta = \frac{x_{e,t}}{x_{a,t}}$. Note that the integration requires $k+1-\sigma > 0$ for $\sigma > 1$.

It is easy to show that $\tilde{x}_{1,t}$ and $\tilde{x}_{2,t}$ completely summarize the information in the distribution of productivity levels $G(x)$ relevant to all aggregate variables. Thus, this economy is isomorphic, in terms of all aggregate outcomes, to one where $N_{1,t}$ plants with productivity $\tilde{x}_{1,t}$ are type I and $N_{2,t}$ plants with productivity $\tilde{x}_{2,t}$ are type II. Accordingly, $\tilde{p}_{1,t} \equiv p_{1,t}(\tilde{x}_{1,t})$ represents the average price of type I plants, and $\tilde{p}_{2,t} \equiv p_{2,t}(\tilde{x}_{2,t})$ represents the average price of type II plants. The price of the dirty aggregate is written as

$$P_t = [n_{1,t}(\tilde{p}_{1,t})^{1-\sigma} + n_{2,t}(\tilde{p}_{2,t})^{1-\sigma}]^{1/(1-\sigma)}.$$

Similarly, denote $\tilde{\pi}_{1,t} \equiv \pi_{1,t}(\tilde{x}_{1,t})$ as the average profit of type I plants, and $\tilde{\pi}_{2,t} \equiv \pi_{2,t}(\tilde{x}_{2,t})$ as the average profit of type II plants. The average profit of all dirty plants is $\tilde{\pi}_t = n_{1,t}\tilde{\pi}_{1,t} + n_{2,t}\tilde{\pi}_{2,t}$. It is easy to show that

$$\tilde{\pi}_{1,t} = \frac{P_t^{\sigma} Q_t}{\sigma}[\frac{\varrho_n}{\tilde{x}_{1,t}}]^{1-\sigma} - w_t f_{a,t} - w_t f \ ,$$

and

$$\tilde{\pi}_{2,t} = \frac{P_t^{\sigma} Q_t}{\sigma}[\frac{\varrho}{\tilde{x}_{2,t}}]^{1-\sigma} - w_t f.$$

The prospective entrants are forward looking, and correctly anticipate their future average profits $\tilde{\pi}_t$ in every period. The discounted present value of an entrant is given by

$$\tilde{v}_{e,t} = [1-G(x_{e,t})]E_t\left(\sum_{s=t+1}^{\infty} R_s \tilde{\pi}_s\right).$$

Plants discount future profits using the household's subjective discounting factor, R_s (to be defined in next subsection). Entry occurs until the average plant value is equalized with the entry cost, leading to the free entry condition $\tilde{v}_{e,t} = w_t f_{e,t}$. This condition holds so long as the mass $N_{e,t}$ of entrants is positive.

After drawing a productivity level x, a plant exits if its present value of profit stream $v_{x,t}$ is negative.

$$v_{x,t} = E_t\left(\sum_{s=t+1}^{\infty} R_s \pi_{x,s}\right),$$

where $\pi_{x,s}$ is the anticipated profit of plant x in period s. Let x_e be the productivity level such that $v_{x_e,t} = 0$. Hence, plants exit after entry if $x < x_e$. The average value of the incumbent plants is

$$\tilde{v}_t = E_t\left(\sum_{s=t+1}^{\infty} R_s \tilde{\pi}_s\right).$$

An Emission Standard The government monitors the plants and sets a standard, s_t, on the emission-output ratio. That is, all plants are required to satisfy $\frac{e_t(x)}{q_t(x)} \leq s_t$. Given the resource price w_t and the standard s_t, the plants choose whether to adopt the new abatement technology, make variable abatement choice, z_t, and set prices according to the constant markup. I consider only the case $s_t < b_n$ here, because the other case $s_t \geq b_n$ is trivial.

The effects of the standard s_t on a plant's choices depend on the plant's productivity level. Recall that $e_t(x) = z_t(x)^{1-h} b \frac{q_t(x)}{x}$ if the plant does not invest in the abatement technology, and $e_t(x) = z_t(x)^{1-h} b_n \frac{q_t(x)}{x}$ if it does. So the standard requires that $\frac{z_t{}^{1-h} b}{x} \leq s_t$ if not investing, and $\frac{z_{n,t}{}^{1-h} b}{x} \leq s_t$ if investing. Note that, if $z_t(x) = 1$, i.e. there are no variable abatement costs, the emission-output ratio is negatively related to the productivity level. Thus, I can classify the plants into five groups[3] according to their choices of abatement methods with a nice future that they are sorted by their productivity levels.

(1) Type 1 plants, $x \geq \frac{b}{s_t}$. These plants do not abate emissions. They have high productivity,

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[3] For illustrating simplicity, I assume that the proportion of exiting plants is very small here, such that only some of the type 5 plants exit.

high output-input ratio, and low emissions-output ratio. They satisfy the standard without any abatement. Let $x_{1,t} = \frac{b}{s_t}$ be the threshold value, the average productivity level for type 1 plants is

$$\tilde{x}_{1.t} = \upsilon x_{1,t},$$

recall $\upsilon = (\frac{k}{k+1-\sigma})^{\frac{1}{\sigma-1}}$.

(2) Type 2 plants, $\frac{b}{s_t} > x \geq x_{2,t}$. These plants incur only variable abatement costs. They have slightly higher emissions-output ratio than the type 1 plants. They need to reduce only a minor amount of emissions to satisfy the standard. So they do not invest in the abatement technology but only use some variable input to reduce emissions. The threshold value of type 2 plants, $x_{2,t}$, is obtained when

$$\frac{P_t^\sigma Q_t}{\sigma}(\frac{\sigma}{\sigma-1}z_t(x)\frac{w_t}{x})^{1-\sigma} - \frac{P_t^\sigma Q_t}{\sigma}(\frac{\sigma}{\sigma-1}\frac{w_t}{x})^{1-\sigma} - w_t f_{a,t} = 0, \tag{2.7}$$

where $z_t(x) = (\frac{b}{s_t x})^{\frac{1}{h-1}}$. The left hand side of equation (2.7) is the difference between the profit if the plant uses only variable abatement input and the profit if the plant invests in the new technology but not uses variable inputs.

The average productivity of type 2 plants is

$$\begin{aligned} \tilde{x}_{2,t} &= [\frac{1}{G(x_1) - G(x_2)} \int_{x_2}^{x_1} x^{\frac{h(\sigma-1)}{h-1}} dG(x)]^{\frac{h-1}{h(\sigma-1)}} \\ &= \varpi x_{2,t}[\frac{1-(\frac{x_{2,t}}{x_{1,t}})^{k-\frac{h(\sigma-1)}{h-1}}}{1-(\frac{x_{2,t}}{x_{1,t}})^k}]^{\frac{h-1}{h(\sigma-1)}}, \end{aligned}$$

where $\varpi = [\frac{k}{k-\frac{h(\sigma-1)}{h-1}}]^{\frac{h-1}{h(\sigma-1)}}$. And the average price of type 2 plants is

$$\tilde{p}_{2,t} = \chi\ \tilde{x}_{2,t}^{-\frac{h}{h-1}},$$

where $\chi = \frac{\sigma}{\sigma-1}(\frac{b}{s_t})^{\frac{1}{h-1}} w_t$. Note that when the variable abatement cost is positive, the average productivity is influenced by h.

(3) Type 3 plants, $x_{2,t} > x \geq x_{3,t}$. These plants invest in the new abatement technology only. These plants have even higher emission-output ratio, so they have a big scale of emission-generation such that is cheaper to reduce emissions by investing the new abatement technology.

The new abatement technology can bring the emission-output ratio below the standard, so no variable abatement costs are incurred. The threshold value $x_{3,t}$ is obtained when

$$x_{3,t} = \frac{b_n}{s_t}.$$

The average level of productivity is

$$\tilde{x}_{3,t} = \upsilon x_{3,t}[\frac{1-(\frac{x_{3,t}}{x_{2,t}})^{k+1-\sigma}}{1-(\frac{x_{3,t}}{x_{2,t}})^{k}}]^{\frac{1}{\sigma-1}}.$$

(4) Type 4 plants, $x_{3,t} > x \ \geq x_{4,t}$. These plants adopt the new technology and use variable input to reduce emissions. The threshold value $x_{4,t}$ is obtained when

$$\frac{P_t^{\sigma} Q_t}{\sigma}(\frac{\sigma}{\sigma-1} z_{n,t}(x)\frac{w_t}{x})^{1-\sigma} - w_t f_{a,t} - \frac{P_t^{\sigma} Q_t}{\sigma}(\frac{\sigma}{\sigma-1} z_t(x)\frac{w_t}{x})^{1-\sigma} = 0, \tag{2.8}$$

where $z_{n,t}(x) = (\frac{b_n}{s_t x})^{\frac{1}{h-1}}$. The left hand side of (2.8) is the difference between the profit when the plant invests in the new technology and also uses some variable input and the profit when the plant uses variable inputs to reduce emissions only. The threshold value is

$$x_{a,t} = x_{4,t} = \{\frac{w_t f_{a,t}\sigma}{P_t^{\sigma} Q_t[\chi_n^{(1-\sigma)} - \chi^{(1-\sigma)}]}\}^{\frac{h-1}{h(\sigma-1)}},$$

where $\chi_n = \frac{\sigma}{\sigma-1}(\frac{b_n}{s_t})^{\frac{1}{h-1}} w_t$. The average productivity level is

$$\tilde{x}_{4,t} = \varpi x_{a,t}[\frac{1-(\frac{x_{a,t}}{x_{3,t}})^{k-\frac{h(\sigma-1)}{h-1}}}{1-(\frac{x_{a,t}}{x_{3,t}})^{k}}]^{\frac{h-1}{h(\sigma-1)}}.$$

(5) Type 5 plants, $x_{a,t} > x \geq x_{e,t}$. These plants incur only the variable abatement costs. They have the highest emissions-output ratio. The total amount of emissions and output are both small. The emission-generation scale is small such that investing in a new abatement technology is too expensive. They abate using variable input only to maintain a low level of producing activity.

$$\tilde{x}_{5,t} = \varpi x_{e,t}[\frac{1-\vartheta^{k-\frac{h(\sigma-1)}{h-1}}}{1-\vartheta^{k}}]^{\frac{h-1}{h(\sigma-1)}}$$

For reasonable parameters all these 5 types of producers exist. For some extreme values of policy and technology parameters, some types may not exist. For example, for a stringent pollution policy it is possible that all the type 5 plants go out of business and even some type 4 or type 3 plants exit.

The profits of plants using different technologies are depicted in Figure 2.1. Line 1 depicts the profit of plants if plants do not reduce emissions. Line 2 is the profit of plants with only variable abatement costs. Line 3 is the profit of plants with only fixed investment in abatement technology. Line 4 is the profit of plants with both fixed and variable abatement costs. Given a level of productivity, a plant will choose the method of abatement that gives highest profit.

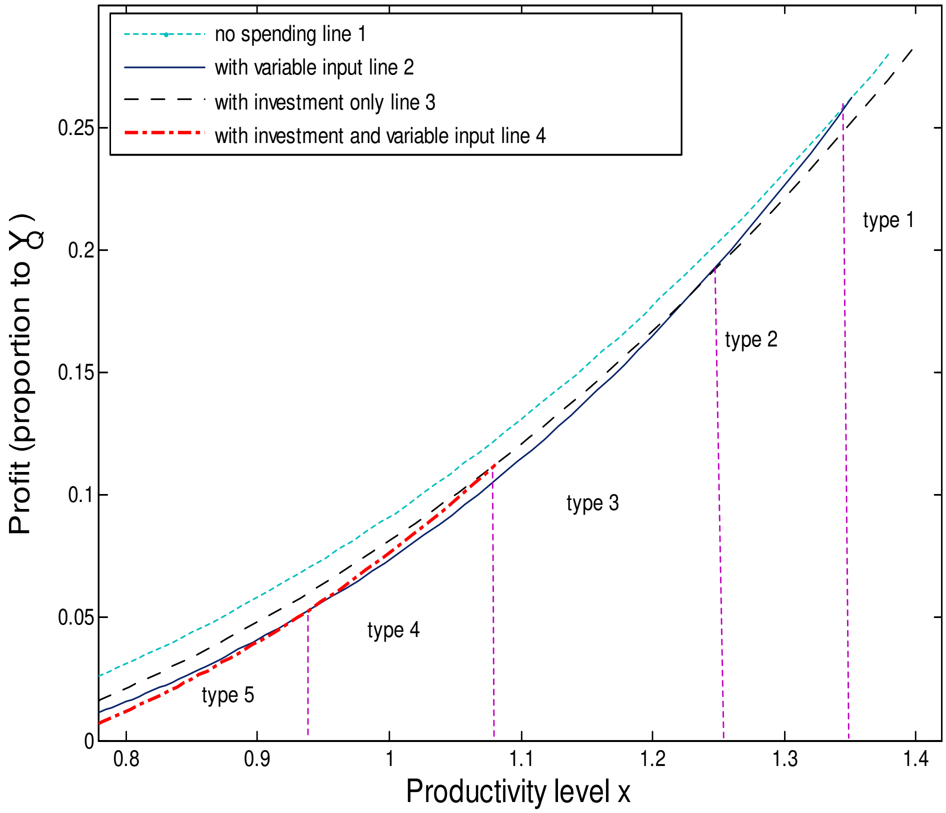

Figure 2.1 The choice of abatement methods w,r.t x

Knowing the threshold values that determine the types of plants, I can now calculate the mass of each type of plants. Denote the mass of type j plants as $N_{j,t}$, the proportion of type j plants is denoted as $n_{j,t}$, and the mass of producing plants is N_t. Thus,

$$n_{1,t} = \frac{N_{1,t}}{N_t} = (\frac{x_{\min}}{x_{1,t}})^k,$$

$$n_{j,t} = \frac{N_{j,t}}{N_t} = [(\frac{x_{\min}}{x_{j,t}})^k - (\frac{x_{\min}}{x_{j-1,t}})^k],$$

for $j = 2,\ 3,\ 4$, and

$$n_{5,t} = \frac{N_{5,t}}{N_t} = [1 - (\frac{x_{e,t}}{x_{a,t}})^k].$$

Denote $N_{a,t}$ as the number of plants who invest in the new abatement technology. Then

$$N_{a,t} = N_{3,t} + N_{4,t}.$$

The average price $(\tilde{p}_{j,t})$ and quantity $(\tilde{q}^s_{j,t})$ of type j plants can be calculated according to the average productivity. The aggregate price of the dirty goods is defined as

$$P_t = [\sum_{j=1}^{5} n_{j,t}(\tilde{p}_{j,t})^{1-\sigma}]^{1/(1-\sigma)}.$$

The average profit is defined as

$$\tilde{\pi}_t = \sum_{j=1}^{5} n_{j,t}\tilde{\pi}_{j,t},$$

where $\tilde{\pi}_{j,t}$ is the average profit of type j plants. The average emissions of type j plants is

$$\tilde{e}_{j,t} = e\ (\tilde{x}_{j,t}),$$

and the aggregate emissions level is

$$E_t = \sum_{j=1}^{5} N_{j,t}\tilde{e}_{j,t}.$$

2.3 The Household's Problem

The representative household enters period t with an endowment of the resource l and mutual fund share holdings A_t, which finance the continuing operation of all pre-existing plants and all new entrants during period t in the dirty sector. The mutual fund pays a total profit in each period that is equal to the total profit of all dirty plants that produce in that period. The period budget constraint of the representative household (in units of the clean goods) is

$$P_t q_t + m_t + (\tilde{v}_t N_t + \tilde{v}_{e,t} N_{e,t}) A_{t+1} = w_t l + (\tilde{v}_t + \tilde{\pi}_t) N_t A_t + T_t, \tag{2.9}$$

where w_t is the resource price denominated in clean goods. During period t, a mass N_t of plants is in operation and pays dividend. The mass of plants evolves according to

$$N_{t+1} = (1-\mu)N_t + (1-\mu)(1-G(x_{e,t}))N_{e,t},$$

since the plants with their productivity levels lower than $x_{e,t}$ exit immediately after entry and a proportion μ of the remaining plants will be hit by the exogenous exit shock at the very end of period t. T_t is the lump sum transfer from the government.

Given the budget constraint (2.9), the household maximizes expected intertemporal utility (2.1). The relative marginal utility of the clean goods and the dirty goods depends on the aggregate level of pollution, that is

$$\frac{U_m}{U_Q} = \frac{1-\alpha}{\alpha}(\frac{m_t}{q_t})^{\rho-1}(\frac{D_t}{\vec{D}})^{\Psi} = \frac{1}{P_t}. \tag{2.10}$$

As pollution level increases, the marginal utility of the clean goods increases relative to the marginal utility of the dirty aggregate. The demand for the dirty goods i is

$$q_{i,t} = q_t[\frac{p_{i,t}}{P_t}]^{-\sigma}. \tag{2.11}$$

The Euler equation for the share is

$$\tilde{v}_t = E_t[R_{t+1}(\tilde{v}_{t+1} + \tilde{\pi}_{t+1})],$$

where $R_s = [\beta(1-\mu)]^{s-t}(\frac{\iota_s}{\iota_t})^{\frac{1}{\rho}-1}\frac{g(D_s)}{g(D_t)}(\frac{m_s}{m_t})^{\rho-1}\frac{N_{t+1}}{N_t}$ is the stochastic subjective discounting factor, for $s > t$, and $\iota_t = (1-\alpha)g(D_t)m_t^{\rho} + \alpha q_t{}^{\rho}$.

2.4 A Steady State Equilibrium

The market clearing conditions are as follows:

(1) the goods markets clear:

$$M_t = m_t \tag{2.12}$$

$$NQ_t = q_t \tag{1.13}$$

(2) the resource market clears:

$$L_{m,t} + N_{n,t} f_{e,t} + N_t f + N_{a,t} f_{a,t} + N \int L_t(x) dG(x) = l \tag{2.14}$$

and (3) the share market clears:

$$A_t = 1 \tag{2.15}$$

Now, it proceeds to define the steady state equilibrium. For all t, and for $x \in [x_{\min}, \infty)$,

Definition 1 *An allocation is comprised of quantities of* $(m_t,\ q_{i,t},\ A_t)$ *for consumers,* $(L_{m,t},\ M_t)$ *for producers in the clean sector, and* $(L_{g,t}(x),\ L_{a,t}(x),\ q_t^s(x),\ e_t(x),\ F_{a,t})$ *for producers in the dirty sector, where* $F_{a,t} = f_{a,t}$ *if the plants invest in the new abatement technology and* $F_{a,t} = 0$ *otherwise;*

Definition 2 *A price system is comprised of* $(w_t,\ P_t,\ p_t(x))$*;*

Definition 3 *A government policy is comprised of* s_t *for the standard or* $(\tau_t,\ T_t)$ *for the tax;*

Definition 4 *A steady state equilibrium is a time-invariant allocation, a time-invariant price system, a law of motion of the aggregate level of pollution with pollution level constant over time, i.e.* $\delta_1 D_{t-1} = E_t$*, and a time-invariant government policy such that (a) given the government policy, the law of motion of the aggregate level of pollution, and the price of resource* w_t *and the relative price* P_t*, the prices* $p_t(x)$ *and the quantities* $(L_{g,t}(x),\ L_{a,t}(x),\ q_t^s(x),\ e_t(x),\ F_{a,t})$ *solve the plant' s problem in the dirty sector; (b) given the price system, the government policy, and the law of motion of the aggregate level of pollution, the allocation solves both the consumer's* *problem and the plant's problem in the clean sector; (c) given the allocation, the price system, and the law of motion of the aggregate level of pollution, the government policy satisfies the budget constraint (2.3); (d) market clearing conditions from (2.12) to (2.15) are satisfied; (e) the free entry condition holds; (f) the distributions for plants' size, emissions, profit, and value are stationary; and (g) consistency between the individual plants' behavior and aggregate variables.*

It is not difficult to show that there is a unique steady state equilibrium given a pollution policy.

3 Calibration

This model integrates emissions into a standard general equilibrium model with heterogenous plants. So I calibrate the model with commonly used empirical evidence found in the literature whenever it is possible. The parameters specific to the paper, most related to emissions, are calibrated to Canadian output, emissions, and abatement expenditure data between 1990 and 2006.

During the period 2000-2006, some regulation on GHG emissions in the near future were anticipated after Canada signed the Kyoto Protocol. Some agreements on reducing GHG emissions between the government and some industries and polluting plants[4] were signed. As a result, some plants have adopted new systems or equipment to reduce GHG emissions although no explicit regulation on reducing GHG was announced.

3.1 Parameters from Conventional Evidence

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[4] Some industries and provinces have signed agreement with the governmnet. For example, April 2005, all major companies of Canada's automobile industry have signed an agreement with the government to voluntarily reduce their greenhouse gas emissions to help Canada meets its commitments under the Kyoto climate protocol. The pact focuses on immediate action to achieve reductions in greenhouse gas emissions.

June 2005, an agreement has been signed between the Government of Canada and the Air Transport Association of Canada to reduce the growth of greenhouse gas emissions in Canada's aviation sector.

December 2006, Ontario announced an Act called Bill 179 for the reduction of greenhouse gas emissions in Ontario.

Table 3.1 lists the values of parameters that are taken to fit the empirical evidence commonly used in the literature. According to Dunne et. al. (1989), the average failure rate of plants in U.S. manufacturing during any five years is 0.391. Hence, the annual failure rate implied by their study is 0.08. This value is used as the exogenous exit rate μ. Again from Dunne et. al. (1989), the annual new entrants rate $\frac{N_n}{N}$ is approximately 0.095. A stationary distribution of plants requires that

$$\frac{N_n}{N} = \frac{\mu}{(1-\mu)(1-G(x_e))}. \tag{3.1}$$

Solving equation (3.1) gives that $G(x_e)$ equals 0.08, where x_e is the threshold value of productivity above which plants produce. The value of $G(x_e)$ will be used to identify the fixed cost of production later.

Table 3.1 The parameters identified according to conventional evidence

	Parameter	Value	Comments
Time preference	β	0.96	real interest rate 4% per year
Exit shock	μ	0.08	Dunne et. al. (1989)
Entry rate	N_n/N	0.095	Dunne et. al. (1989)
Emissions decay rate	δ_1	0.008	Kolstad (1996)
Threshold of emissions stock	$\bar{D}$	32.0	1965 pollution stock
Initial level of emissions stock	D_{-1}	32.1	1990 pollution stock

The decay rate of GHG emissions is 0.083 per decade found in the literature (Kolstad (1996) among others), which implies an annual decay rate δ_1 of 0.008 . The threshold value $\bar{D}$ is taken as the 1965's stock level of GHG (1965 is usually taken as a reference point, Nordhaus (1993) and Kolstad (1996)). I set $\vec{D}$ to equal 32 gigaton CO_2 equivalent.[5] Given $\bar{D}$, D_{-1} is calculated as 32.1 gigaton at the beginning of 1990.

3.2 Parameters Matching Canadian Data

The preference parameters depend on the definition of the dirty sector and the clean sector. The definition of the dirty sector is provided in the appendix. The clean to dirty goods sales ratio $\frac{Y_m}{Y_Q}$,

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[5] The literature (e.g. Nordhaus (1993), and Kolstad (1996)) used 667 gigaton as the stock of GHG for U.S. in 1965. Since Canada emits roughly 0.1 percent of that in US and this paper cut off the emissions other than industrial emissions, which is about 52% percent of total GHG, 4.8% of 667 is used as $\vec{D}$.

the pollutant stock D_t, and the relative price P_t during 1990 and 2006 are used to calibrate α, ρ, and Ψ. The relative price of dirty goods to clean goods is constructed (see appendix for detail). In order to identify α, ρ, and Ψ, I rewrite equation (2.5) as

$$\ln \frac{Y_m}{Y_Q} = \frac{1}{1-\rho} \ln(\frac{1-\alpha}{\alpha}) + \frac{\Psi}{1-\rho} \ln(\frac{D_t}{\vec{D}}) + \frac{\rho}{1-\rho} \ln P_t. \tag{3.2}$$

Given the data on P_t, D_t, and $Y_{m,t}/Y_{Q,t}$, the preference parameters can be estimated by using equation (3.2).

Equation (3.2) predicts that $Y_{m,t}/Y_{Q,t}$ decreases in the relative price P_t since the dirty goods and the clean goods are complements, $-1 < \rho < 0$. The coefficient ρ determines the magnitude of this effect. The higher is the absolute value of ρ, the lower is the substitutability, and the larger is the effect of the price change on the ratio $Y_{m,t}/Y_{Q,t}$. Equation (3.2) also predicts that an increasing pollution level leads to consumers demanding more clean goods, which leads to a higher ratio $Y_{m,t}/Y_{Q,t}$. Ψ influences the impact of D_t on $Y_{m,t}/Y_{Q,t}$. A higher Ψ implies a higher disutility from pollution for consumers and therefore a stronger effect. Ψ should be higher than $|\rho|$. If not, D_t would have a positive effect on utility. Also, it is not reasonable to have a value of Ψ much higher than $|\rho|$ since the GHG emissions have not caused a major disutility. The disutility parameter is assumed to be less than $|\rho| * 1.5$. The average value of $Y_{Q,t}/Y$ in the data is 0.38. The value of the exogenous share of dirty goods α in the model should not be far away from the dirty goods share $Y_{Q,t}/Y$ in the data. Given these restrictions, I estimate parameters α, ρ and Ψ by seeking the estimates that minimize the divergence between the model and the data, and I find $\alpha = 0.36$, $\rho = -0.4$, and $\Psi = 0.45$ give the best fit. The model simulated $\ln \frac{Y_{m,t}}{Y_{Q,t}}$ and the data are depicted in figure 3.1.

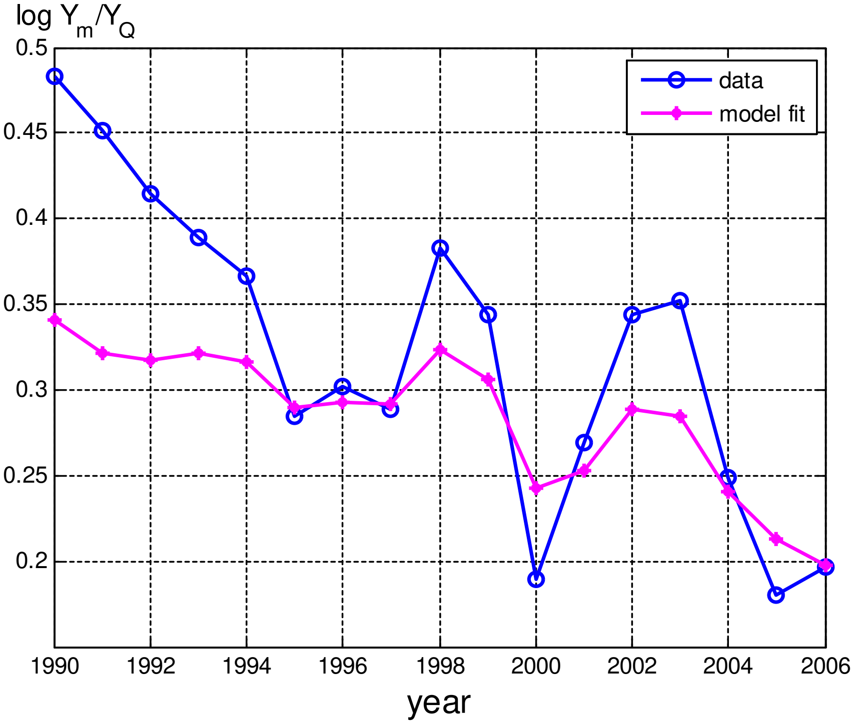

Figure 3.1 Model's fit

In order to calibrate the abatement-related parameters h, b_n and f_a, I split the data into three sub-periods: 1990-1994, 1995-1999, and 2000-2006. In the first period, there was no emission-reduction effort. During the second sub-period, the Kyoto Protocol was signed and Canada committed to reduce GHG emissions to a level 6% below the 1990 level between 2008 - 2012. Accordingly, some plants started using new abatement technologies during 2002 and 2006. So I calibrate the parameters characterizing the basic economy without emission-reduction in the first period and calibrate the abatement technology related parameters in the third period. Since in the model plants will adopt new abatement technology only if there are some enforcement to reduce emissions, I assume that there is an identical emission standard in the third period to generate the emission-reduction activities reported by Environment Canada.

(1) In the first period, there is no evidence in the data of any reduction of GHG emissions. So this period is used to identify the parameter that describe the basic economic structure without emission-reduction technology. The parameters to calibrated are the average productivity in the

clean sector, X, the lowest productivity in the dirty sector, $x_{\min}$, the productivity dispersion parameter, k, the fixed production cost, f, the fixed entry cost, f_e, the substitution parameter among dirty goods, σ, the emission factor, b, and the magnitude of the economy measured in resources in the first period, l_1.

X is normalized to 1. The ex ante average productivity in the dirty sector is also normalized to 1. That is $\int_{x_{\min}}^{\infty} x dG(x) = 1$. $x_{\min}$ can be identified given the value of k and $G(x) = 1 - (\frac{x_{\min}}{x})^k$. Other parameters are identified by simulating the model to match the moments in the first period. The dirty goods sales share is used to find k. The exit and entry rates and equilibrium condition mentioned above implied that $G(x_e) = 0.08$, which in turn implies that $f = 0.0475\frac{Y_Q}{wN}$ (0.0066 in the numerical model), where Y_Q/N is the average avenue of the dirty plants. f_e is calculated from the free entry condition given the average profits of dirty plants $\frac{1}{\sigma}Y_Q/N - wf$, that is $f_e = \frac{\beta(1-\mu)}{1-\beta(1-\mu)}(1 - G(x_e))(\frac{1}{\sigma}\frac{Y_Q}{wN} - f) = 1.5\frac{Y_Q}{wN}$, where $\frac{\sigma}{\sigma-1}$ is the mark up. Using the relationship $b = \frac{\sigma}{\sigma-1}\frac{E}{Y_Q}$ from integrating emissions across plants and the moment of the emission-sales ratio $\frac{E}{Y_Q} = 2.15$ in the data, I get $\sigma = 3.8$ and $b = 2.92$ kilo-ton CO_2 emissions equivalent per million dollars. I set the endowment in this period l_1 to be 0.35 trillion dollars in order to equate the level of emissions generated in the model to the average level of emissions in the data during 1990 and 1994. The values of these parameters are listed in table 3.2.

Table 3.2 The parameters identified in period without emission-reduction

	parameter	value	targets or constraints (1990-94)
clean sector productivity	X	1	normalization
minimum productivity	$x_{\min}$	0.706	$\int_{x_{\min}}^{\infty} x dG(x) = 1$
emissions factor	b	2.92	emissions sales ratio E/Y_Q, 2.15
substitution among dirty goods	σ	3.8	$b = \frac{\sigma}{\sigma-1}\frac{E}{Y_Q}$
fixed production costs	f	0.0066	$G(x_e) = 1 - \frac{\mu}{(1-\mu)\frac{N_n}{N}} = 0.08$
fixed entry costs	f_e	$1.5Y_Q/N$	free entry condition
productivity dispersion	k	3.4	dirty goods sales share, 0.39
resource	l_0	0.35	emissions level, 0.299 gigaton

(2) In the third period, the emissions-sales ratio in the dirty sector declines dramatically, $\frac{E}{Y_Q} = 1.96$. In the dirty sector, 24% of dirty plants reported using new system or equipment

to reduce Greenhouse Gas emissions. This is, by assumption, because of enforcing an emission standard s. To achieve the emission-sales ratio in this period, s has to be $0.74b$. The plants that adopted new abatement technology also reported the impact of using the new abatement technology. According to the reported impact of the technology in 2002, I set $b_n = 0.8b$.[6] The fixed cost of adopting the new abatement technology $f_{a,t}$ is approximately 1.3% of the dirty goods sales according to the two facts that the capital expenditure on abatement in 2002 is 0.31% of the dirty goods sales and there were 24% of plants who invested in the new abatement technology. The percentage of plants that invested in new abatement technologies reported during the third period is used to find h. h is found to be 5.8, which implies that a one percent increase in operating abatement expenditure reduce emissions by 4.8%. This means that for a plant with an average productivity level it is more efficient to use the new abatement technology than to use the variable inputs to reduce emissions. The same expenditure could reduce emissions by 20% if the plant uses the new abatement technology. Finally, I set the endowment l to be 0.492 trillion dollars in order to equate the level of emissions generated in the model to the average level of emissions in the data during 2000 and 2006. The values of these parameters are listed in table 3.3.

Table 3.3 The parameters identified in period with emission-reduction

	parameter	value	targets or constraints (2000-2006)
abatement tech.	h	5.8	investment rate, $N_a/N = 0.24$
emission factor with new tech.	b_n	$0.8b$	survey on abatement tech.
fixed cost on new tech.	f_a	$0.013Y_Q/N$	capital expenditure in abatement
standard	s	$0.74b$	emissions sales ratio E/Y_Q, 1.96
resource	l	0.492	emissions level, 0.368 gigaton

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[6] Among the plants reporting adoption of a new abatement technology, 13% reported significant reduction of GHG emissions, 44% reported mediam reduction, and 44% reported small reduction. I interpret significant effect as 40%, medium effect as 24%, and small effect as 10%. This leads to an effect of 20% on average. See appendix table II

4 Quantitative Experiment

4.1 Standard versus Tax

Emission standards and taxes generate different incentives for plants to reduce their emissions. As shown in section 2, under an emission tax the plants with the highest productivity will adopt the discrete abatement technology, while under the emission standard the plants with the middle levels of productivity will adopt the abatement technology. This difference in abatement choices induced by different policies affects the abatement efficiency and production efficiency and therefore the relocation of resources across plants.

Emission standards and taxes also increase the relative price of dirty goods to different extends. The emission tax is a price instrument. As plants incorporate emission taxes into their production plan, the price of dirty goods increases directly. The emission standard is a quantity instrument. It does not change price directly. Instead, it increases the amount of resources required to produce one unit of dirty goods, including the resources used to reduce emissions in order to satisfy the standards, and therefore it increases the price of their products to cover the additional variable abatement costs. Recall that the price is set according to a fixed mark-up over the variable costs. The different degrees of price distortion caused by different policies affect the reallocation of resources between the clean and the dirty sector.

The following experiment compares the effects of the emission tax and standard policies in terms of aggregate outputs and relative prices for an equal amount of emission-reduction. Key variables are listed in table 4.1. The unit for emissions E is gigaton. As shown in table 4.1, the price of dirty goods is higher under the emission tax. As a result, a higher quantity of clean goods but a less quantity of dirty goods are produced (demanded) under the tax policy compared to under the standard. The quantities of resources allocated to the dirty sector are higher under the standard policy. The average productivity in the dirty sector is also higher under the standard due to that a higher proportion of low productivity plants exits from the industry. These effects are more pronounced if a larger proportion of emissions is reduced as shown in table 4.2.

Table 4.1 Compare the models under the tax and under the standard

	tax $\tau = \$3.33/per\ ton$	standard $s = 0.74b$
m	0.3185	0.3183
q	0.1857	0.1863
E	0.3680	0.3680
p	1.0169	1.0110
N	1.2977	0.9495
N_a/N	0.82%	24.41%
$G(x_e)$	8.55%	12.08%
resources in dirty sector L_x	0.1379	0.1388
average productivity	0.7427	0.7450
value of utility function	0.2018	0.2020

Table 4.2 Compare the models under the tax and under the standard

(under more stringent policies)

	tax $\tau = \$8.00/per\ ton$	standard $s = 0.64b$
m	0.3184	0.3175
q	0.1853	0.1867
E	0.3601	0.3601
p	1.0288	1.0143
N	1.2861	0.9495
N_a/N	3.48%	25.95%
$G(x_e)$	8.61%	13.01%
resources in dirty sector L_x	0.1376	0.1396
average productivity	0.7425	0.7474
value of utility function	0.2047	0.2049

The value of the utility function is slightly higher under the standard policy. This result is different from the literature without the consideration of productivity dispersion, in which emission tax is more efficient. The main reason that the standard policy could be more efficient is that the average productivity of the dirty sector could be higher under the emission standard compared to that under the emission tax. Under the emission standard, the very high productivity plants do not incur additional abatement costs since they are born clean. As other plants incur additional costs and increase their prices, these very high productivity plants gain additional market shares. The very low productivity plants have to exit from the industry since they are most inefficient in reducing emissions. As a result, the dirty goods are produced by more productive plants under the emission standard.

4.2 Comparison of Results with and without Productivity Dispersion

This subsection studies the economic and environmental performance of an emission tax in an economy without productivity dispersion relative to economies with different degrees of productivity dispersion. In order to have a fair comparison, a model without productivity dispersion is constructed in a way such that the outputs of both the clean goods and the dirty goods are as same as in the model with productivity dispersion specified above, in which the productivity dispersion parameter k takes a value of 3.4. In the two models, all the parameters are the same with the exception of the productivity parameters, which are listed in table 4.3. Using the same method, I also construct two models with different degrees of productivity dispersion: $k = 4$ and $k = 3.2$. Table 4.3 shows that the economy with higher degree of productivity dispersion ($k = 3.2$) generates less emissions in order to produce the same amount of outputs.

Table 4.3 The initial values of variables in models with and without productivity dispersion

	dispersion parameters			
	$k = \infty$ (no dispersion)	$k = 4$	$k = 3.4$ (benchmark)	$k = 3.2$
m	0.3185	0.3185	0.3185	0.3185
q	0.1857	0.1857	0.1857	0.1857
E ($gigaton$)	0.3952	0.3721	0.3680	0.3618
$\tau(\$/ton)$	3.33	3.33	3.33	3.33
X	0.9856	0.997	1	1.002
the mean of x	1.3720	1.184	1	0.882

4.2.1 Counterfactuals

The Estimates of Emissions under Taxes In the models with different degrees of productivity dispersion, imposing an emission tax reduces different amounts of emissions. Figure 4.1 depicts the proportion of emissions estimated by the models with different degrees of productivity dispersion after imposing ad valorem emission taxes. As seen from the figure, starting from the initial level of emissions (normalized to 1) and increasing the emission tax, the proportion of emissions reduced in the economy without dispersion is larger than that in the economy with dispersion up until a threshold value of the tax rate, after which the opposite is the case. In the simulated economies, the threshold value of the tax rate is around 33$ per ton of emissions. When the tax rate is lower, the model without dispersion underestimates the reduction of emissions. When the tax rate is above the threshold value, the model without dispersion overestimates the reduction of emissions.

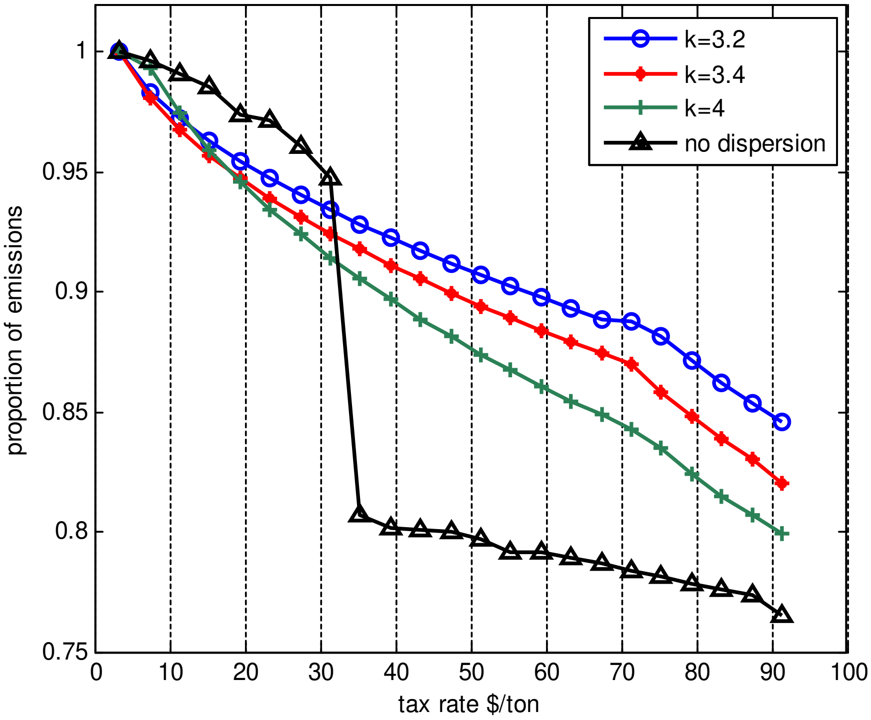

Figure 4.1 Tax rates and emissions reduction

The reason of this difference in the estimates of emissions is as follows. Each plant chooses whether to adopt the new abatement technology contingent on its productivity. In the economy without dispersion, all the plants have an identical level of productivity. When the tax rate is low, no plants adopt the new abatement technology. As the emissions tax increases, the prices of dirty goods increase and less quantities are demanded. The emissions decline slightly and it comes from the reduction of dirty-goods production. When the tax rate is high enough, all the plants invest in the abatement technology. This conversion of abatement methods generates a sharp drop of emissions when the threshold value of tax rate is reached in figure 4.1. In the economy with productivity dispersion, the very high productivity plants invest in the new abatement technology when the tax rate is low. As the tax rate increases, plants with lower levels of productivity gradually invest in the abatement technology. Hence, the reduction of emissions is smooth.

Figure 4.1 also compares the reduction of emissions in economies with different degrees of productivity dispersion. Starting from the initial levels of emissions, the economy with a higher degree of productivity dispersion reduces a slightly larger proportion of emissions under a moderate tax rate. As the tax rate increases, the economy with a higher degree of productivity dispersion reduces less emissions. The reason is simply shown in table 4.4. The higher degree of productivity dispersion, the smaller investing rate of the abatement technology under the same tax rate.

Table 4.4 The reduction of emissions in models with different degrees of productivity dispersion

	$\tau = 88.05$ (\$/ton)			
	$k = 3.2$	$k = 3.4$	$k = 4$	no dispersion
emission reduction	-15.34%	-17.08%	-20.00%	-24.50%
variable abatement costs	0.00079	0.00088	0.00079	0.00003
investing rate Na/N	20.45%	28.30%	48.14%	100%

The Effects of Targeting Emissions The welfare consequences of pollution policies in an economy with heterogeneous plants and in the economy with homogeneous plants may be significantly different. Table 4.5 provides the effects of reducing emissions by 3%, 20%, and 25% below the initial levels of emissions. Table 4.6 provides the estimated costs of both production and abatement in each model.

To reduce 3% of emissions, the economy with productivity dispersion is more efficient. In the economy without productivity dispersion, no plants adopt the new abatement technology, so the reduction of emissions comes completely from the reduction of dirty goods production. The price of the dirty goods increases by a much higher proportion than that in the economy with productivity dispersion. This distortion induced by the emission tax causes the economy without productivity dispersion to lose more GDP or the consumption of goods.

Table 4.5.a The effects of targeting emissions

	$k = 3.4$			
reduction of emissions	initial level	-3%	-20%	-25%
tax rate (\$/ton)	3.33	10.59	92.96	100.75
consumption $\triangle\%$[7]	–	-0.14%	-1.95%	-2.44%
welfare	100%	102.03%	114.32%	118.83%
M	0.3185	0.3184	0.3201	0.3174
Q	0.1857	0.1851	0.1748	0.1752
dirty sector real output / input	1. 3692	1. 3696	1. 3733	1. 3745
P \$	1.0169	1.0354	1.2320	1.2490
real GDP[8]	0.5073	0.5066	0.4979	0.4956
aggregate GDP $\triangle\%$	–	-0.14%	-1.85%	-2.31%
$G(x_e)$	0.0855	0.0864	0.0948	0.0954
investing rate Na/N	0.82%	3.26%	27.84%	28.12%
exit rate	8.07%	8.29%	9.32%	9.33%

To meet the Kyoto Protocol, Canada needs to reduce Greenhouse Gas emissions by 6% below the 1990 level or more than 25% from the current level. In an economy with heterogeneous plants, there are two difficulties in curbing the GHG emissions: (1) a large percentage of low productivity plants will not adopt the new abatement technology and (2) some low productivity plants will go out of business if the tax is imposed, leading to more waste of sunk entry costs. When the tax rate increases to 100 \$ per ton, the percentage of plants that adopt the new abatement technology is just 28%. The dirty sector reduces emissions using less efficient methods. Reducing emissions by 25% costs the economy with heterogeneous plants by additional 0.87% of GDP compared to the economy with homogenous plants. In the economy with heterogeneous plants, as the tax rate increases, the exit rate increases and the entry cost increases.

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[7] It is the welfare cost measured by the percentage of consumption that has to be raised to achive the same welfare level as in the initial state, keeping the emissions level as 0.3680.

[8] The real GDP is calculated using the price in the initial states.

Table 4.5.b The effects of targeting emissions

	no dispersion			
reduction of emissions	initial level	-3%	-20%	-25%
tax rate (\$/ton)	3.33	29.80	39.90	90.37
consumption $\triangle\%$[9]	–	-0.26%	-0.90%	-1.67%
welfare	100%	101.93%	115.65%	120.07%
M	0.3185	0.3227	0.3140	0.3177
Q	0.1857	0.1801	0.1857	0.1781
dirty sector real output / input	1.3705	1.3705	1.3705	1.3705
P \$	0.9907	1.0610	1.0671	1.1837
real GDP[10]	0.5087	0.5074	0.5041	0.5003
aggregate GDP $\triangle\%$	–	-0.26%	-0.90%	-1.65%
$G(x_e)$	0	0	0	0
investing rate Na/N	0%	0%	100%	100%
exit rate	8%	8%	8%	8%

Table 4.6.a and table 4.6.b show the decomposition of costs in the economy with and without productivity dispersion respectively. In the model with productivity dispersion, the variable abatement costs increase dramatically in order to reduce $20\% - 25\%$ of emissions, while the investment expenditure in abatement technology is limited by the proportion of high productivity plants that choose to invest in the new abatement technology. In the model without productivity dispersion, all the plants invest in the new abatement technology and reduce emissions more efficiently, so they save some variable abatement inputs.

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[9] It is the welfare cost measured by the percentage of consumption that has to be raised to achive the same welfare level as in the initial state, keeping the emissions level as 0.3680.

[10] The real GDP is calculated using the price in the initial states.

Table 4.6.a The decomposition of costs

	$k = 3.4$			
emissions reduction	initial level	-3%	-20%	-25%
L_m trillion \$	0.3185	0.3184	0.3201	0.3174
L_g trillion \$	0.1379	0.1374	0.1294	0.1297
$L_a$trillion \$	0	0	0.0019	0.0038
investment in abatement	0.0000	0.0001	0.0008	0.0008
entry cost	0.0269	0.0274	0.0310	0.0316
fixed cost	0.0087	0.0087	0.0087	0.0088
total expenditure	0.4920	0.4920	0.4919	0.4921

Table 4.6.b The decomposition of costs

	no dispersion			
emissions reduction	initial level	-3%	-20%	-25%
L_m trillion \$	0.3231	0.3274	0.3186	0.3223
L_g trillion \$	0.1354	0.1313	0.1354	0.1299
$L_a$trillion \$	0	0	0	0.0006
investment in abatement	0	0	0.0026	0.0028
entry cost	0.0242	0.0253	0.0262	0.0279
fixed cost	0.0093	0.0080	0.0092	0.0085
total expenditure	0.4920	0.4920	0.4920	0.4920

4.2.2 The Distributional Effects

In an economy with productivity dispersion, a uniform emission tax has two side effects in opposite directions. On the one hand, it leads to a resource reallocation flowed from low productivity plants (including exiting plants) to high productivity plants. This increases the overall productivity of the producing plants. On the other hand, it also increases the aggregate sunk entry cost since some low productivity plants exit from the industry and the turnover of plants increases. In the model, the second effects tend to dominate such that the quantity of dirty goods declines. For example, when the tax rate is 10.59$ per ton, tables 4.5.a and table 4.6.a show that the increased entry costs account for most of the losses of dirty goods.

Reallocation of resources and market shares When the emission tax applies, the high productivity plants invest in the new abatement technology and their shares of emissions decrease; the low productivity plants do not invest in the abatement technology and their shares of emissions increase. The shares of output for high and low productivity plants move in opposite directions. The high productivity plants increase their market shares as a result of the tax. Hence, the overall productivity in the dirty sector increases. Figure 4.2 and 4.3 show this distributional effect.

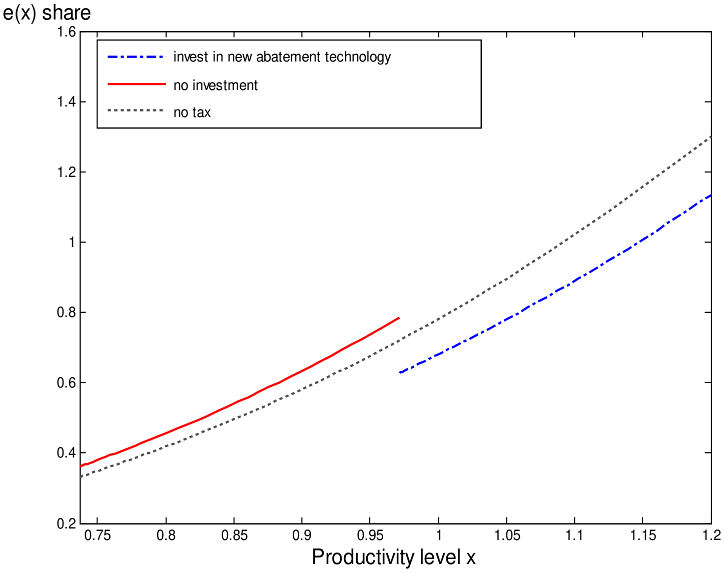

Figure 4.2 The share of emissions under an emissions tax

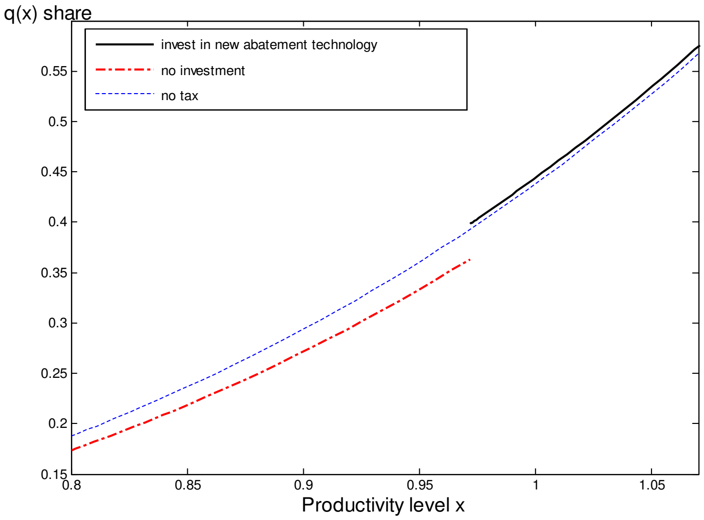

Figure 4.3 The share of output under an emissions tax

The Exit of Plants A stringent pollution policy forces more plants to exit from the dirty sector. It reduces the welfare in two ways. First, table 4.5.a shows that the proportion of producing plants $(1-G(x_e))$ decreases as the tax rate increases in the economy with productivity dispersion. This means that the variety of goods decreases. Second, as the turnover of plants increases the sunk entry costs climbs. As a result, less resources are available to produce.

The controversial "grand-fathering" policy has the potential to prevent some sunk entry costs because it grants the existing plants looser standards on emissions and hence it does not drive as many low productivity plants out of business. However, it is at the expense of aggregate productivity. The overall effect depends on which partial effect dominates.

4.3 Models without Exit

To understand better the sources of the different welfare consequences of an emission tax in the economies with and without productivity dispersion, I also study the models without exit.

4.3.1 Re-Calibrate Some Parameter Values

The model with productivity dispersion In order to exclude the exit, I have to assume that there is no fixed cost in production and there is no death of plants. The profit margin is enlarged by these adjustments. The free entry condition still holds although there is no entry in the equilibrium. As the profit margin increases, the entry cost implied by the free entry condition also increases. The value of f_e rises to $6.316Y_Q/N$. Since the profit margin is increased, I let the average productivity in the dirty sector to be lower in order to keep the dirty goods sales share at 0.39 without adjust the value of productivity dispersion parameter k, but the value of $x_{\min}$ becomes 0.6354.Other parameters are kept as in the model with exit calibrated above. Finally, to keep the emissions at the level 0.3680 gigaton, the resources l is adjusted to 0.4447.

The model without productivity dispersion The model without productivity dispersion is constructed by adjusting the parameters governing the average productivity levels in both the clean and the dirty sector. The key variables generated by the new models are listed in table 4.7.

Table 4.7 The initial values of variables in models with and without productivity dispersion

	dispersion parameters	
	$k = \infty$ (no dispersion)	$k = 3.4$
m	0.3068	0.3068
q	0.1628	0.1628
E $(gigaton)$	0.3940	0.3680
$\tau(\$/ton)$	3.3300	3.3300
X	0.9904	1.0
the mean of x	1.2066	0.9

4.3.2 Quantitative Experiments

After eliminating the exit, the reduction of consumption or GDP is less in general in order to reduce the same proportion of emissions. It is mainly because of the saved entry costs. Besides this significant change, other arguments about the comparison between the economy with and without productivity dispersion in the case with exit hold in general. When the target is to reduce 3% of emissions, it is more costly in the economy without productivity dispersion; when the target is to reduce 20%-25% of emissions, it is less costly in the economy without productivity dispersion. The key variables are listed in table 4.8.a and table 4.8.b.

Table 4.8.a The effects of targeting emissions - $k = 3.4$

		$k = 3.4$		
reduction of emissions	initial level	-3%	-20%	-25%
tax rate (\$/ton)	3.33	10.59	93.92	101.92
consumption $\triangle\%$	$-$	-0.04%	-1.21%	-1.54%
welfare	100%	102.09%	114.86%	119.48%
M	0.3068	0.3071	0.3111	0.3088
Q	0.1628	0.1623	0.1542	0.1547
dirty sector real output / input	1.3692	1.3692	1.3693	1.3702
P \$	1.1600	1.1821	1.4116	1.4317
real GDP	0.4956	0.4954	0.4900	0.4882
aggregate GDP $\triangle\%$	$-$	-0.04%	-1.13%	-1.49%
investing rate Na/N	0.83%	3.38%	30.10%	30.10%

Table 4.8.b The effects of targeting emissions - no dispersion

		no dispersion		
reduction of emissions	initial level	-3%	-20%	-25%
tax rate (\$/ton)	3.33	29.80	43.8	91.18
consumption $\triangle\%$	$-$	-0.34%	-0.53%	-1.15%
welfare	100%	101.81%	116.08%	120.37%
M	0.3068	0.3108	0.3042	0.3080
Q	0.1628	0.1579	0.1628	0.1570
dirty sector real output / input	1.3705	1.3705	1.3705	1.3705
P \$	1.1151	1.2118	1.2291	1.3541
real GDP	0.4944	0.4932	0.4921	0.4894
aggregate GDP $\triangle\%$	$-$	-0.26%	-0.46%	-1.01%
$G(x_e)$	0	0	0	0
investing rate Na/N	0%	0%	100%	100%

4.4 The Welfare in Transition

It is usually with more interest to know the transition of an economy after a tax shock, especially if it takes a long time to evolve to the new steady state. For simplicity, this section uses the models without exit.

I start with the study of the tax shocks that bring the economy to a steady state with the maximum welfare. So I find the optimal steady-state first. The steady-state welfare-maximizing tax rates in the models with and without productivity dispersion are calculated and the corresponding steady state equilibria are reported in table 4.9.a and 4.9.b.

Table 4.9.a The optimal tax rate in the model - $k = 3.4$

	initial level	optimal level
tax rate ($/ton)	3.33	112.1
emissions (gigaton)	0.3680	0.2560
consumption $\triangle\%$	$-$	-2.00%
welfare	100%	125.00%
M	0.3068	0.3061
Q	0.1628	0.1552
dirty sector real output / input	1. 3692	1. 3720
P $	1.1600	1.4554
real GDP	0.4956	0.4861
aggregate GDP $\triangle\%$	$-$	-1.92%
investing rate Na/N	0.83%	30.10%

Table 4.9.b The optimal tax rate in the model - no dispersion

	initial level	optimal level
tax rate ($/ton)	3.33	112.1
emissions (gigaton)	0.3940	0.2560
consumption $\triangle\%$	–	−1.96%
welfare	100%	131.34%
M	0.3068	0.3061
Q	0.1628	0.1552
dirty sector real output / input	1. 3705	1. 3720
P $	1.1151	1.4554
real GDP	0.4944	0.4853
aggregate GDP $\triangle\%$	–	−1.84%
investing rate Na/N	0%	100%

4.4.1 Transition to the Optimal Steady State

Starting from the current state of the economy, suppose the steady state welfare-maximizing tax rate is imposed and let the economy evolve to the optimal steady state. As shown in figure 4.4, it takes over 300 years for the economy to evolve to the welfare-maximizing steady state. The steady state welfare-maximizing tax rate over-shots the dirty sector such tha the dirty sector output falls below its future steady state level. As the emissions stock decreases over time, the dirty sector recovers itself, but the clean sector declines over time. After imposing the steady state optimal tax rates, the emissions fall by 33% below the current level right after the policy shock, which is below the level in the future steady state.

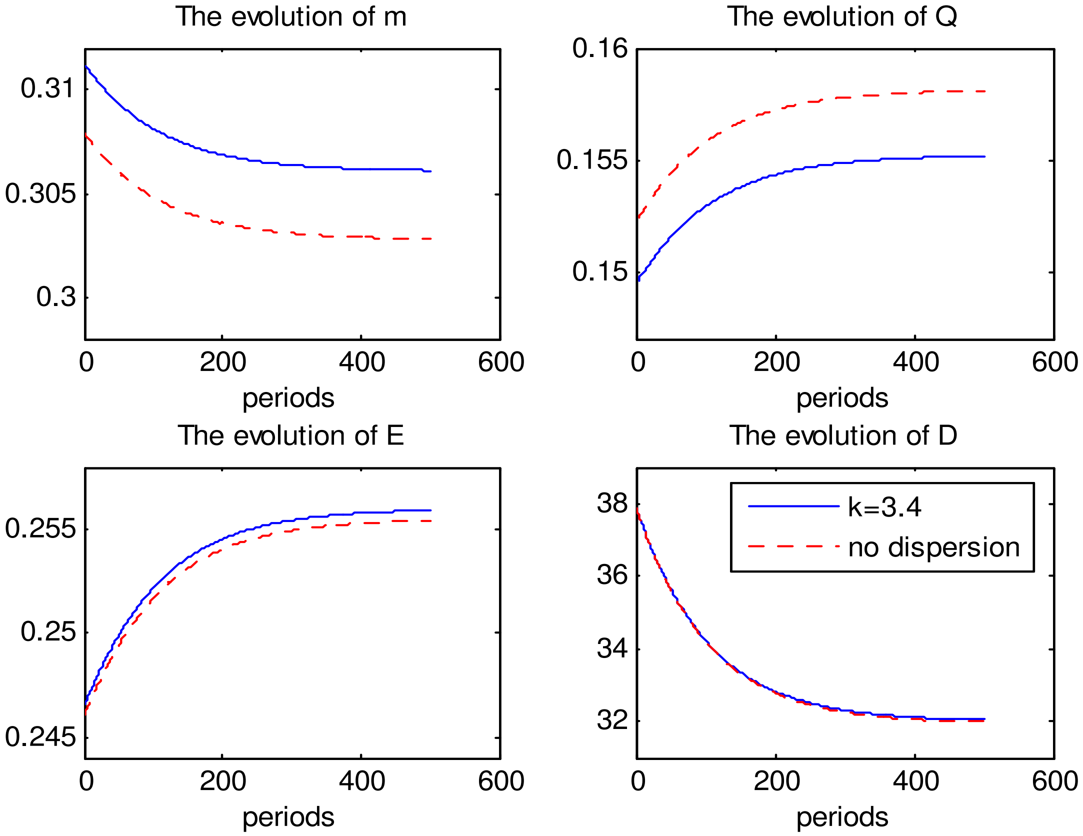

Figure 4.4 The transition of variables under optimal steady state tax rates

4.4.2 Welfare-Improving Dynamic Taxes and Consumption Losses

Imposing the steady state welfare-maximizing tax rates, it still takes over 300 years to achieve the steady state. It is welfare improving to reduce emissions more aggressively in the early periods given that the emission stock causes disutility before the steady state is reached. In other words, the optimal tax rates should be higher in the earlier periods. So I assume that the government first imposes a constant tax rate that is higher than the steady state optimal rate and lets the emission stock decline. Once the emissions stock is low enough to sustain the optimal steady state, the government change the tax rate to the steady state optimal and keeps it forever. Such a tax instrument has an optimal rate 160$ per ton of emissions in the early years, and 112.1$per ton of emissions in the later periods in the model with $k = 3.4$, and an optimal rate 156$ per ton of emissions in the early years, and 109.9$per ton of emissions in the later periods in the model with no productivity dispersion. It takes only about 60 years for the economy to reach the optimal steady state. The lifetime utility increases by 0.45% in the model with $k = 4$ and by 0.47% in the model with no productivity dispersion. The transition dynamics are shown in figure 4.5 below.

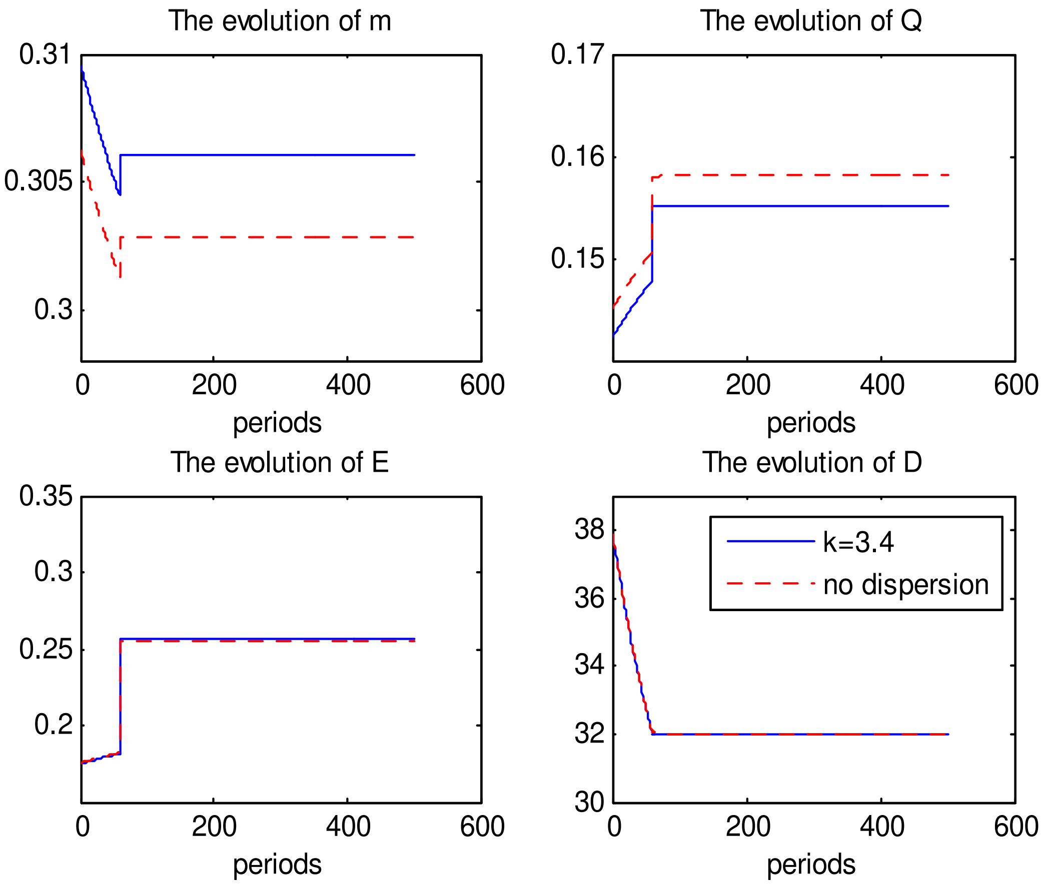

Figure 4.5 The transition of variables under optimal two stages tax rates

Although the lifetime utility increases, the representative consumer consumes less consumption goods in the economy with productivity dispersion. The present value of the discounted real GDP decreases by 1.61%. The real GDP is a sum of the amount of the clean goods and the dirty goods multiplied by the relative price, i.e. $GDP = m + pQN$. The relative price used here is the price in the optimal steady state. As shown in the experiments above, the GDP loss is approximately equal to the consumption loss.

Surprisingly, the present value of the discounted real GDP in the model without productivity dispersion does not change. From both the consumption perspective and the environmental perspective, it is better to reduce emissions aggressively in the early stage if there is no productivity dispersion. But in the model with productivity dispersion, the consumption losses from reducing emissions aggressively in the early stage is large. This is because the different allocations of resources in the two economies: the economy with no productivity dispersion produces more dirty goods and less clean goods than the economy with productivity dispersion; the earlier increase of the dirty goods consumption accounts more in the economy with no productivity dispersion.

4.4.3 Implementing the Kyoto Protocol

If the government lets the tax rate be 3.33\$ per ton of emissions as specified in the benchmark economy, the lifetime utility of a representative consumer is lowered by 2.19%, but the present value of the discounted GDP is increased by 4.49% , compared to the two-stages optimal tax rates. The transition of the economy is depicted in figure 4.6.

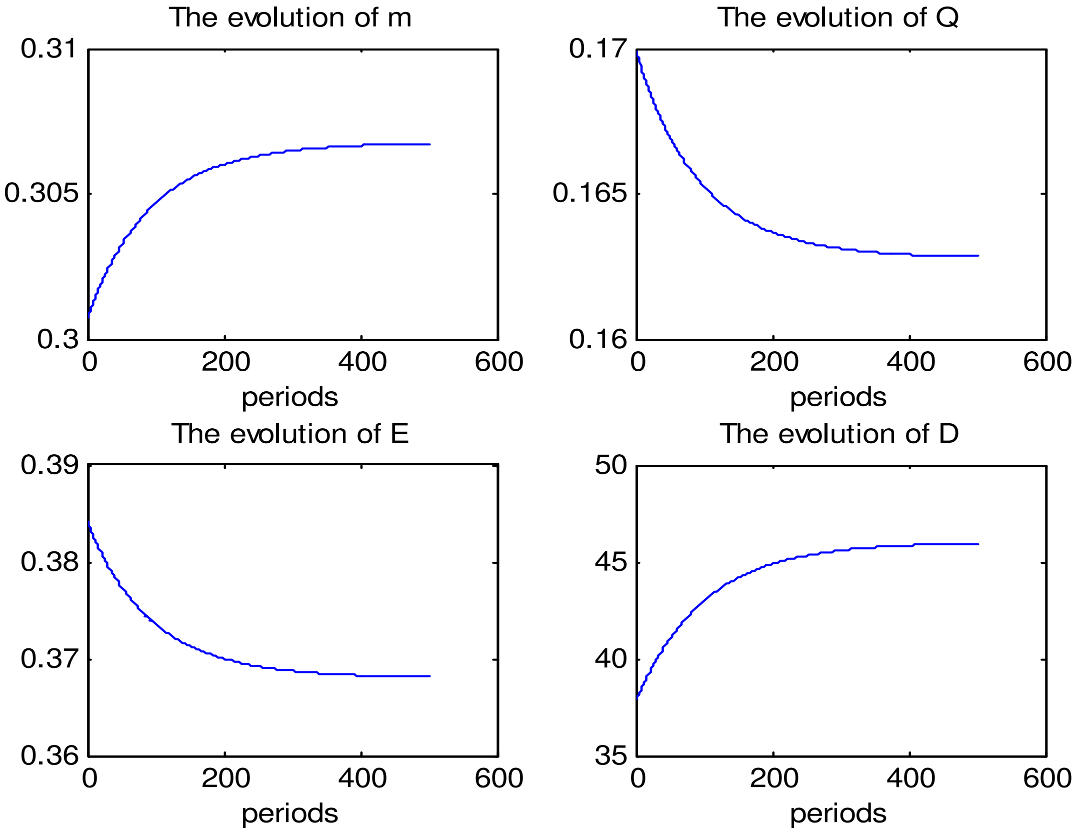

Figure 4.6 The transition of variables without further action

According to the Kyoto Protocol Canada should reduce emissions by 25.6% of the current level. So I find a tax rate, 100.57$ per ton of emissions, that could achieve this target. The transition of the economy is shown in figure 4.7. The lifetime utility of a representative consumer is 0.77% lower compared to that under the two-stages optimal tax rates. However, the present value of the discounted GDP is increased by 2.33%. Compared to the economy without further actions, to implement the Kyoto Protocol costs 2.16% of the real GDP in the dynamic model.

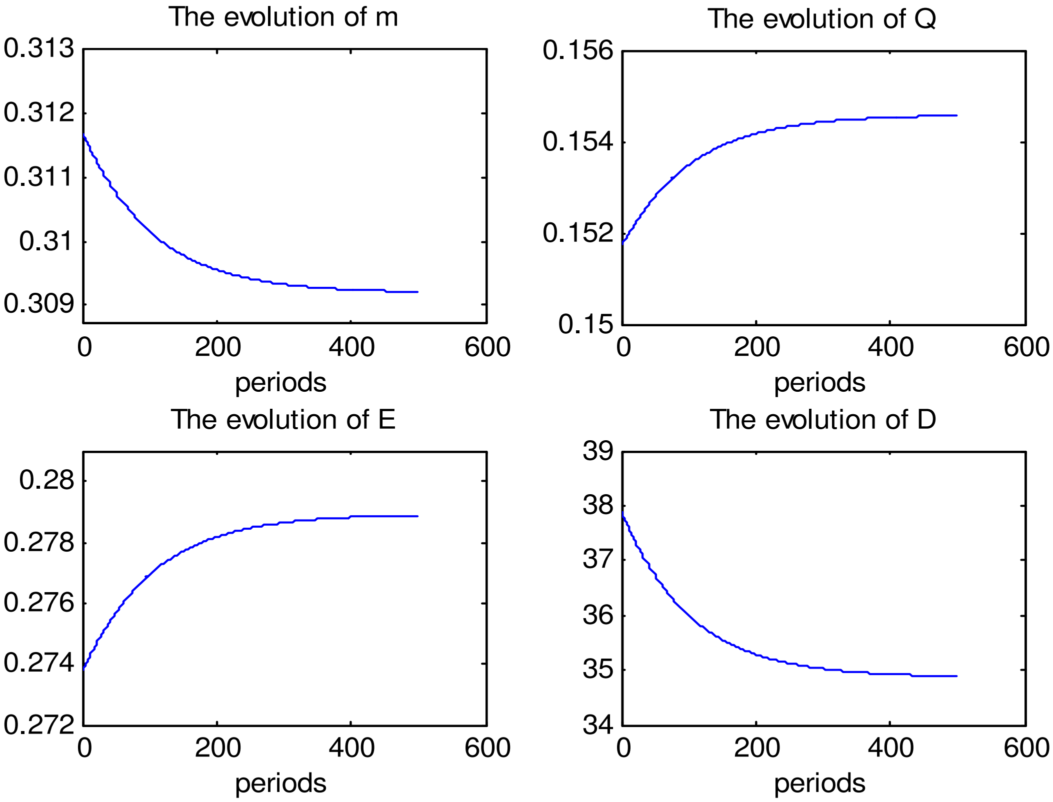

Figure 4.7 The transition of variables implementing Kyoto Protocol

5 Conclusion

The paper has developed a general equilibrium model with polluting heterogeneous plants. The polluting plants are subject to idiosyncratic productivity shocks, contingent on which they optimally choose whether or not to adopt a new abatement technology for a given pollution policy. The emission tax and emission standard induce different groups of plants measured by their productivity levels to adopt the new abatement technology. Under the emission standard, the very high productivity plants are born cleaner and they do not abate; the very low productivity plants exit due to inefficiency in achieving the emission standard. The average productivity of the dirty sector could be higher under the standard and therefore the emission standard could be more efficient. This is different from the literature that do not consider the productivity dispersion, in which emission tax is more efficient.

In the model with productivity dispersion across plants, a uniform emission tax has the following effects: (1) it induces high productivity plants to invest in the new abatement technology; (2) it leads to a relocation of resources from low productivity plants to high productivity plants; (3) it drives some low productivity plants out of business; (4) it moves resources from the dirty sector to the clean sector. The quantified model shows how productivity dispersion influences the impacts of pollution policies. The paper finds that a higher degree of productivity dispersion and therefore the existence of a large mass of low productivity plants increases the costs of curbing air emissions when the emission-reduction requires those low productivity plants to respond. This is because those low productivity plants are small in scale and not optimal to choose the more efficient technology to reduce emissions. Their average abatement costs are high. The aggregate cost of reducing GHG emissions by 20% from the current level in Canadian industries is about 2 times as large as that in a similar economy without productivity dispersion.

The paper also compares the transition after a pollution policy shock in the models with and without productivity dispersion. A surprising result is that the economy with productivity dispersion is much more costly to reduce emissions more aggressively in the early stage. Finally, in the model with productivity dispersion, to implement the Kyoto Protocol costs 2.16% of real GDP in a dynamic model. The magnitude of this cost is similar to the one calculated in the steady state.

The paper evaluates pollution policies in an economy with heterogeneous plants. It calls attention to the different reactions of plants to an uniform pollution policy and the resulted efficiency problem.

Appendix: Data Description

1. Define the clean sector and the dirty sector. There are 16 industries whose abatement costs per employee are less than 1000$ according to the Environment Canada. The emissions from these 16 industries account for about 90% of all the industrial emissions. These 16 industries are defined as dirty industries: Forestry and Logging (NAICS 113000), Oil and Gas Extraction (NAICS 211000), Mining (NAICS 212000), Electric Power Generation, Transmission and Distribution (NAICS 221110),, Natural Gas Distribution (NAICS 221200), Food manufacturing (NAICS 311000), Beverage and Tobacco Products (NAICS 312000), Wood Products (NAICS 321000), Pulp, Paper, and Paperboard Mills (NAICS 3221000), Petroleum and Coal Products (NAICS 324000), Chemicals (NAICS 325000), Non-Metallic Mineral Products (NAICS 327000), Primary Metals (NAICS 331000), Fabricated Metal Products (NAICS 332000), Transportation Equipment (NAICS 336000), and Pipeline Transportation (NAICS 486000).

2. The investment in new abatement technology during 2000-2002.

Table.I. Adoption of new or significantly improved systems or equipment to reduce GHG emissions by industry [11]

	Introduced new or significantly improved systems or equipment	Impact on emissions		
		small	medium	large
Industry	percentage			
Logging	11	71	29	0
Oil and Gas Extraction	65	31	57	12
Mining	18	70	30	0
Electric Power Generation	29	45	23	32
Natural Gas Distribution	58	0	71	29
Food Manufacturing	10	59	41	0
Beverage and Tobacco Products	16	60	40	0
Wood Products	14	50	36	14
Paper Manufacturing	35	40	36	24
Petroleum and Coal Products	39	62	38	0
Chemicals	18	55	33	13
Non-Metallic Mineral Products	18	46	31	23
Primary Metals	21	30	51	19
Fabricated Metal Products	18	43	50	7
Transportation Equipment	23	59	32	9
Pipeline Transportation	71	17	80	3
Total	24	44	44	13

3. Construct the economy. The emissions from these 16 industries account for about 50% of the total emissions in Canada. Since this paper focuses on only industrial emissions, the emissions

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[11] This table includes reported data only. Figures may not add up to totals due to rounding.

(1) Adoption of new or significantly improved systems or equipment within a three year period, 2000-2002.

(2) Respondents who answered Yes to the adoption of new or significantly improved systems or equipment were asked to rank the impact on greenhouse gas emission reductions as being small, medium or large.

Source: Statistics Canada, Environment Accounts and Statistics Division.

from transportation, agriculture, residence, and other sources are excluded. The aggregate GDP in this paper is therefore cut off about 50% of the total Canadian GDP to match the 50% emissions. This is done with an assumption that the GDP and emissions are proportional. The GDP of the clean and dirty goods sectors used in estimating the parameters in the relationship between GDP ratio and price ratio in equation (3.2) are nominal GDP adjusted by the price indices constructed below.

4. Construct the relative price. The relative price is the ratio between the price of the dirty aggregate and the price of the clean goods. The dirty goods price is constructed as a GDP-weighted average of 12 dirty goods: Electric power generation, Petroleum and Coal Products, Fabricated Metal Products, Food Manufacturing, Beverage and Tobacco Products, Wood Products, Pulp, Paper, and Paperboard Mills, Primary Metals, Fabricated Metal Products, Gasoline, Chemical and Chemical Products, and Transportation Equipment. The clean goods price is constructed as a weighted average of 3 clean goods: new houses, electrical and communication products, and farm product with wights $54\%, 30\%$ and 16%, respectively. The relative price at the initial date, i.e. 1990, is normalized to 100.

Table II. The price indices for clean goods and dirty goods

Year	Price index - clean goods	Price index - dirty goods
1990	100	100
1991	94	98
1992	93	99
1993	95	100
1994	97	104
1995	98	112
1996	98	111
1997	97	111
1998	98	104
1999	98	108
2000	99	129
2001	102	130
2002	106	125
2003	108	128
2004	113	150
2005	114	162
2006	122	181

5. The emissions data for Canada from 1990 to 2006 come from the Greenhouse Gas Emissions National Inventory Report (NIR) by Environment Canada. The GDP data come from Statistics Canada, CANSIM II. The industrial level emissions and GDP data come from the Canadian Industrial End-use Energy Data and Analysis Centre and CANSIM II.

6. Total operating and capital expenditures on environmental processes and technologies to reduce greenhouse gas emissions by industry, 2004. Source: Statistics Canada, Environment Accounts and Statistics Division.

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