

**Trade and the Environment with Pre-existing Subsidies:  
A Dynamic General Equilibrium Analysis\***

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## Abstract

Countries that wish to erect trade barriers have a variety of instruments at their disposal. In addition to tariffs and quotas, countries can offer tax relief, low interest financing, reduced regulation, and other subsidies to domestic industries facing foreign competition. In a trade agreement, countries typically agree to reduce not only tariffs, but also subsidies. We consider the effect of a free trade agreement on pollution emissions. We show that while reducing tariffs may indeed increase output and pollution, reductions in some subsidies required by the trade agreement reduce pollution in general equilibrium for reasonable parameter values. Reducing subsidies has three effects on pollution: (1) reducing subsidies to firms reduces pollution-causing capital accumulation, (2) if subsidized firms are more pollution intensive, then reducing subsidies moves capital and labor from more to less pollution intensive firms, and (3) reducing subsidies concentrates production in more productive firms, increasing output and thus pollution. We derive straightforward conditions for which (1) and (2) outweigh (3). We then calibrate the model to China in 1997, which is prior to implementing the reforms specifically required by the US-China World Trade Organization (WTO) Bilateral Agreement. Our model predicts that pollution emissions in China are up to 22.9% lower than a baseline in which China does not enter the WTO, without any pollution abatement policy changes or environmental side agreements.

## 1 Introduction

Countries that wish to erect trade barriers have a variety of instruments at their disposal. In addition to tariffs and quotas, countries can offer tax relief, low interest financing, reduced regulation, and other subsidies to domestic industries facing foreign competition. The political process is unlikely to produce a uniform tariff. Instead, countries with high trade barriers employ a complex mixture of all these instruments, resulting in significant distortions. In a trade agreement, countries typically agree to reduce not only tariffs, but also subsidies. For example, subsidies to exporting industries violate WTO rules.<sup>1</sup>

The main claim of our paper is that reductions in domestic subsidies implied by some trade agreements have significant effects on pollution emissions. These effects are associated with a country's opening to trade and, therefore, cannot be ignored when considering the effects of trade agreements on pollution. Reducing subsidies has three effects on pollution. First, a reduction in subsidies to firms reduces pollution-causing capital accumulation. Second, if subsidized firms, industries, and/or state owned enterprises (SOEs) are more pollution intensive, then reducing subsidies moves capital and labor from more to less pollution intensive firms. Third, reducing subsidies concentrates capital and labor in more productive firms, increasing output and thus pollution. We derive conditions under which the first two effects outweigh the third. In our most conservative calibration, our main condition is satisfied for three of four pollutants studied.

Thus even if world tariff reductions cause pollution-intensive production to increase in a country, overall pollution may still fall because the tariff effect is more than offset by the reduction in pollution caused by the reduction in subsidies. Indeed, we calibrate the model to China in 1997 and find that, after reducing subsidies required by the WTO agreement, the equilibrium path of total suspended particulates (TSP) in our model converges over time to a steady state 17.6% lower than a baseline economy in which no subsidies are reduced. Similarly, steady state chemical oxygen demand (COD) is 7.6% lower, and sulfur dioxide (SO<sub>2</sub>) is 22.9% lower. Total suspended solids, TSS, rise by 0.5%. The reduction in pollution occurs without any environmental side agreements or abatement policy changes.

There is a large theoretical literature on trade and the environment.<sup>2</sup> Research has

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<sup>1</sup>Specifically, subsidies specific to an individual or group of firms, products, or industries which are either contingent on export performance ("prohibited") or have adverse effects on member industries ("actionable") are not allowed. Member countries may bring suit to have such subsidies removed or be allowed to retaliate. See Annex 1A, Agreement on Subsidies and Countervailing Measures of the WTO's legal document on the Uruguay Round Agreements. Bagwell and Staiger (2005) argue the criteria for challenging domestic subsidies in the WTO is weak enough so that governments can in principle challenge any positive subsidy.

<sup>2</sup>Survey papers include Copeland and Taylor (2004), Kolstad and Xing (1996), Rauscher (2001), and Ulph (1997).

focused on three possible channels whereby a reduction in trade barriers can affect environmental quality. Following Copeland and Taylor (2004) and others, we denote the idea that a reduction in trade barriers causes pollution intensive production to shift from countries with relatively stringent regulation to countries with relatively weak regulation the *pollution haven hypothesis* (PHH).<sup>3</sup> The PHH predicts that, following a reduction in trade barriers, pollution rises in the country with weak regulation and falls in the country with stringent regulation. A second channel, the *factor endowment hypothesis* says that since pollution is capital intensive, reducing trade barriers should cause pollution intensive industries to move to the more capital intensive country, usually the more developed country. In the third channel, increases in income caused by a reduction in trade barriers affect both pollution intensive production and abatement spending.

Mani and Wheeler (1997), Low and Yeats (1992), Ratnayake (1998), and others find some evidence in favor of the PHH. These studies suffer from lack of pollution data in less developed countries, and so must instead classify industries according to their emissions intensity in the US and then correlate output in pollution intensive industries to openness. On the other hand, Birdsall and Wheeler (1992) and Lucas, Wheeler, and Hettige (1992) find that pollution intensity is relatively lower in more open economies. In general, environmental regulations do not seem to be a major factor in plant location decisions.

As Antweiler, Copeland, and Taylor (2001) note, both theoretical and empirical studies generally take pollution regulations and/or income to be exogenous. For example, countries may tighten environmental regulations after an inflow of pollution intensive capital. Even if pollution regulations are identical across countries, production moves to its most efficient location, causing production and pollution to increase. The resulting increase in income may itself cause countries to increase abatement or otherwise tighten pollution regulations, as has been noted in the Environmental Kuznets Curve (EKC) literature (Grossman and Krueger 1995). Antweiler, Copeland, and Taylor (2001) study the effect of reducing trade barriers on SO<sub>2</sub> concentrations. They decompose the effect into scale, composition, and technique effects. Reducing trade barriers causes output to rise, which increases pollution (the scale effect). However, the increase in income also results in increased abatement spending, reducing pollution (the technique effect). Finally, a reduction in trade frictions causes the country exporting the dirty good to specialize in that good, increasing pollution (the composition effect). They also avoid the data problems present in previous studies by using data on SO<sub>2</sub> emissions from the Global Environmental Monitoring database. They find a particularly strong technique effect, implying that trade improves the quality of the environment by

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<sup>3</sup>That is, we are not considering the *pollution haven effect*, which deals with the effect of environmental regulations on trade flows.

raising income and abatement. This channel has perhaps the best support in the data. However, the EKC does not seem to be robust to changes in empirical specification or across pollutants (Harbaugh, Levinson, and Wilson 2002, Stern and Common 2001), so the result may not generalize to pollutants other than SO<sub>2</sub>.

We propose here an entirely new channel by which free trade agreements may affect the environment: the free trade agreement acts as a catalyst by which governments reduce pollution-causing subsidies.<sup>4</sup> As in Antweiler, Copeland, and Taylor (2001), a scale effect exists in that reducing subsidies causes output to rise, which increases pollution. Our model by assumption has no changes in abatement policy. Yet if subsidies fall we still have a technique effect. If subsidized firms are more pollution intensive, then as production moves from the subsidized sector to the non-subsidized sector (hereafter we call the non-subsidized sector the private sector), overall pollution intensity falls. Our calibration to China indicates the technique effect is quite strong in practice.

Our model is consistent with, apparently contradictory, empirical findings that after a trade agreement output in pollution intensive industries may increase at the same time as pollution intensity decreases, without any assumptions on abatement policy. We reconcile these two observations by means of a shift of production from highly polluting subsidized firms onto less polluting private firms.<sup>5</sup> Finally, our results are consistent with the strong technique effect found by Antweiler, Copeland, and Taylor (2001). They find increases in income are associated with large reductions in pollution intensity. Our finding of another reason why pollution intensity may fall following a trade agreement helps explain the magnitude of the overall technique effect in the data.

The related literature on how subsidies to industry affect the environment is very sparse.<sup>6</sup> Since almost all countries have industrial policies which favor some industries, this lack of attention is quite surprising. To understand pollution in such a setting requires a theory of firms and industry structure with subsidies. Bajona and Chu (2005) provide a computational model where private and state owned firms coexist. We use this idea to develop a general theory of subsidies and pollution. The industry structure consists of private firms and subsidized firms, facing domestic and foreign competition. Subsidized firms have restrictions

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<sup>4</sup>The subsidies channel is not direct result of changes in trade flows. Nonetheless, since reductions in subsidies are part of free trade agreements, the subsidies effect must be considered when examining the effects of trade agreements on the environment.

<sup>5</sup>Copeland and Taylor (2004) discuss other possible cases where output rises but pollution falls as countries reduce trade barriers.

<sup>6</sup>Barde and Honkatukia (2004) discuss the extent of subsidies in environmentally sensitive industries and discuss a few channels by which subsidies may affect the quality of the environment. van Beers and van den Bergh (2001) show in a static, partial equilibrium setting how subsidies can increase output and pollution in a small open economy. The only established literature is on agricultural subsidies and the environment (see for example Antle, Lekakis, and Zanas (1998)).

on the number of people they can lay off (Yin 2001), which we model as a minimum labor requirement. In exchange, subsidized firms receive low interest loans from the government or state owned banks (modeled as an interest rate subsidy) and receive direct subsidies to cover the negative profits that result from the use of an inefficient mix of capital and labor. Finally, subsidized firms have lower total factor productivity (TFP) relative to private sector firms. We prove the existence of an equilibrium in which subsidized firms and private firms co-exist with the share of production of subsidized firms determined endogenously by the subsidies, labor requirements, and technology difference.<sup>7</sup> Subsidies thus affect pollution by changing the share of production of the subsidized sector.

Although the literature on subsidies and the environment is sparse, there is a related empirical literature on SOEs and the environment. Wang and Jin (2002) find SOEs in China are more pollution intensive than private firms (by up to a factor of 10). In addition, Gupta and Saksena (2002) find that SOEs in India are monitored for environmental compliance less often than private firms. Wang, Mamingi, Laplante, and Dasgupta (2002) find that SOEs in China enjoy more bargaining power over environmental compliance than private firms. Pargal and Wheeler (1996) find SOEs in Indonesia are more polluting than private firms, even after controlling for age, size, and efficiency. Hettige, Huq, and Pargal (1996) survey studies with similar results. Galiani, Gertler, and Schargrotsky (2005) find that privatization of water services in Argentina improved health outcomes. However, Earnhart and Lizal (2002) find an inverse relationship between pollution intensity and percentage of state ownership among recently partially privatized firms in the Czech Republic in their preferred model. The latter two studies focus on a change in ownership, which does not necessarily imply a change in subsidies.<sup>8</sup>

In our model, subsidies affect pollution through two main mechanisms. The first mechanism, which we call *capital and labor resource reallocation effects*, is static in nature and shows the effect of the reallocation of capital and labor from private to subsidized firms that subsidies induce. First, direct subsidies increase equilibrium employment in subsidized firms, causing output to become more concentrated in subsidized firms. Second, this increase in employment causes capital to flow to the subsidized sector, further concentrating output in subsidized firms. If subsidized firms are more pollution intensive, these two effects cause pollution to increase. Finally, as resources concentrate in the subsidized sector the equilibrium

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<sup>7</sup>We are ignoring many other types of subsidies, see Barde and Honkatukia (2004) for a partial list. Nonetheless, the subsidies we consider are the main focus of trade agreements such as the US-China bilateral agreement.

<sup>8</sup>It is well known that recently privatized SOEs retain a close relationship to the state and thus possibly their subsidies. A trade agreement is different from privatization in that the former reduces subsidies, while the latter changes ownership.

marginal product of labor and capital in the subsidized sector decreases, reducing overall output and pollution by concentrating labor and capital in the low-productivity subsidized sector. We derive sufficient conditions on parameter values for which the first two effects are stronger than the third.

The second mechanism, which we call the *capital accumulation effect*, is dynamic in nature and affects intertemporal decisions. On one hand, subsidies to firms directly increase overall demand for capital. On the other hand, the decline in overall productivity caused by the concentration of capital in the subsidized sector tends to reduce demand for capital. We show that the former effect is stronger so the return to capital rises, causing the economy to over-accumulate capital, which causes pollution to rise over time with subsidies.

## 2 A Theory of Pollution, Subsidies, and Trade

In this section, we consider a simplified version of the computational model in Section 4 in order to derive some analytic results on how subsidies affect pollution emissions. The intuition gleaned from the theory carries over directly to the computational model, but the additional features of the computational model allow for better quantitative predictions.

### 2.1 Firms

Private and subsidized firms differ in four aspects: productivity, pollution intensity, ability to choose their labor input, and cost of capital. Productivity differences are taken as exogenous, with subsidized firms having TFP equal to  $A_G$ , while private firms have TFP equal to  $A_P$ . Private and subsidized firms produce using a constant returns to scale technology  $F$  and are competitive price takers.<sup>9</sup> Their production functions differ only in their TFP levels.

We assume employment at subsidized firms is constrained to be greater than or equal to a minimum labor requirement,  $l_G$ , established by the government. In exchange for keeping the level of employment, the government covers any losses through direct subsidies. If the labor requirement binds, subsidized firms use an inefficient mix of capital and labor and earn negative profits. Subsidized and private firms then co-exist if subsidized firms receive enough direct cash subsidies from the government to earn zero profits.<sup>10</sup> Therefore, let  $S = -\pi_G$  be the direct subsidy, where  $\pi_G$  are the (negative) profits of subsidized firms excluding the direct subsidy and  $\Pi_G = \pi_G + S = 0$  are the profits including the direct subsidy. To save on notation, we suppress the time  $t$  subscripts where no confusion is possible.

Let  $l_P$  be the labor demand of the private sector. The representative household is endowed

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<sup>9</sup>Some subsidized firms clearly have monopoly power. This assumption is discussed in Section 6.

<sup>10</sup>In the absence of subsidies, in a competitive equilibrium only the firm with the highest TFP operates.

with one unit of labor every period, which is supplied inelastically. Therefore, in equilibrium  $l_G + l_P = 1$ .

Subsidized firms receive a second subsidy, a discount on their rental rate of capital, which we call an interest subsidy. If we denote the rental rate of capital for private firms as  $r$  (in terms of domestic goods), the rental rate of capital for subsidized firms is  $(1 - s)r$ , where  $s$  is the subsidy rate. This subsidy can be interpreted as either the government guaranteeing repayment of funds borrowed by subsidized firms, SOEs borrowing at the government's rate of interest, or as the government steering household deposits at state owned banks to subsidized firms at reduced interest rates.<sup>11</sup>

The objective of both private and subsidized firms is to maximize profits taking prices and government policies as given. If the subsidized firm is privately owned, then profit maximization is clearly reasonable. But even if the subsidized firm is state owned, evidence exists for the idea that managers of SOEs are given incentives consistent with profit maximization.<sup>12</sup> Our theory is not based on differences in firm ownership, since whether households or firms own the capital is irrelevant as long as all firms maximize profits. Instead, our theory is based on the subsidies that firms with a close relationship to the state enjoy.

The problem of a subsidized firm consists of maximizing profits subject to the labor requirement imposed by the government and the subsidy on capital:

$$\pi_G = \max_{K_G} A_G F(K_G, l_G) - (1 - s)rK_G - wl_G. \quad (2.1)$$

Here  $K_G$  and  $K_P$  are the parts of aggregate capital allocated to the subsidized and private sectors, respectively, and  $K = K_G + K_P$  is the aggregate capital stock per person. Let subscripts on functions denote partial derivatives. The first order condition which determines the part of the capital stock allocated to the subsidized sector is:

$$(1 - s)r = A_G F_k(K_G, l_G). \quad (2.2)$$

The problem for private firms is standard:

$$\pi_P = \max_{K_P, l_P} A_P F(K_P, l_P) - rK_P - wl_P. \quad (2.3)$$

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<sup>11</sup>The latter interpretation is more reasonable for developing countries. All three interpretations are consistent with households renting capital.

<sup>12</sup>For China, Yin (2001) assumes SOEs maximize profits, based on the results from Choe and Yin (2000). However, by making this assumption we are ignoring agency issues and other problems associated with SOEs (see for example Gupta 2005, Shleifer and Vishny 1994).

The equilibrium rental rate and wage rate,  $w$  (also in domestic goods), are:

$$r = A_P F_k (K - K_G, 1 - l_G), \quad (2.4)$$

$$w = A_P F_l (K - K_G, 1 - l_G). \quad (2.5)$$

Let  $F$  be constant returns to scale in  $K$  and  $l$ , have positive and diminishing marginal products, satisfy  $F(0, l) = F(K, 0) = 0$ , and satisfy the Inada conditions in each input. Then equations (2.2), (2.4), and (2.5) have a unique solution  $K_G(K, A_G/A_P(1-s), l_G)$ ,  $r(K, A_G/A_P(1-s), l_G)$ , and  $w(K, A_G/A_P(1-s), l_G)$ . The labor constraint is binding (subsidized firms hire more labor than is efficient) if and only if  $w > A_G F_l(K_G, l_G)$ . If subsidized firms hire less labor than is efficient, they make positive profits and the direct subsidy is a tax. Since this case is not interesting, we assume the constraint binds. A sufficient condition for the constraint to bind is:<sup>13</sup>

$$(1-s) A_P > A_G. \quad (2.6)$$

We can also show:

$$\frac{\partial K_G}{\partial s} > 0, \quad \frac{\partial K_G}{\partial l_G} > 0, \quad 0 < \frac{\partial K_G}{\partial K} < 1, \quad (2.7)$$

$$\frac{\partial r}{\partial s} > 0, \quad \frac{\partial r}{\partial l_G} < 0 \Leftrightarrow \text{condition (2.6)}, \quad \frac{\partial r}{\partial K} < 0, \quad (2.8)$$

$$\frac{\partial w}{\partial s} > 0, \quad \frac{\partial w}{\partial l_G} > 0 \Leftrightarrow \text{condition (2.6)}, \quad \frac{\partial w}{\partial K} > 0. \quad (2.9)$$

Thus changes in the subsidies change the share of capital, labor, and output of the subsidized sector, which in turn drives many of the results of the paper. Consider first a decrease in the interest subsidy rate. A decrease in the interest subsidy rate implies a reallocation of capital from the subsidized sector to the private sector. Further, a decrease in the interest subsidy rate decreases the total demand for capital, hence the interest rate must fall to bring demand for capital back up to the supply. Similarly, a fall in the demand for capital implies a lower demand for labor as well so the wage rate must also fall. Consider second a fall in the labor requirement. Although a fall in the labor requirement will cause labor to move from the subsidized sector the private sector by definition, it is not immediate that the wage

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<sup>13</sup>For a Cobb-Douglas production function with capital share  $\alpha$ , the constraint binds if and only if  $(1-s)^\alpha A_P > A_G$ .

rate falls. Instead, the fall in the labor requirement causes the subsidized sector to reduce demand for capital as well. If the private sector sees sufficiently little increase in capital relative to the increase in labor, wages fall, but it could be that a large change in capital in the private sector causes demand for labor to rise, pushing up wages. The overall effect depends on the relative TFP of the two sectors.

Finally, the share of capital allocated to the subsidized sector adjusts to equate the after-subsidy returns in the two sectors. The interest subsidy causes capital to flow to the subsidized sector, reducing the marginal product of capital in that sector and raising the marginal product of capital in the private sector until the after-subsidy returns are equated. Thus, the equation which governs the fraction of capital allocated to the subsidized sector is:

$$(1 - s) A_P F_k(K - K_G, 1 - l_G) = A_G F_k(K_G, l_G). \quad (2.10)$$

## 2.2 Households

### 2.2.1 Aggregate Good

Households enjoy consumption of an aggregate good  $c$ , which is a composite of the domestic produced good,  $X$ , and the imported good,  $M$ . Let  $u(c)$  denote the per period utility, which we assume is strictly increasing and concave, twice-continuously differentiable, and satisfies the Inada conditions. The objective of households is:

$$\max \sum_{t=0}^{\infty} \beta^t u(c_t). \quad (2.11)$$

Let  $X_D$  denote the part of domestic production that is consumed domestically, and  $X_F$  denote the part of domestic production that is consumed abroad. Households use an Armington aggregator to combine  $X_D$  domestic goods and  $M$  foreign goods into  $Y_C$  aggregate goods:<sup>14</sup>

$$Y_C = X_D^\mu M^{1-\mu}. \quad (2.12)$$

We can interpret  $\mu$  as the share of domestic production consumed domestically, absent domestic tariffs. The composite good can also be used for investment. Notice that because each country specializes in one good, we are ruling out effects due to comparative advantage like the PHH and the factor endowment hypothesis. This allows us to examine the effect of

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<sup>14</sup>The Armington aggregator assumption is made in order to be able to match trade data. In order to simplify the analytical derivations, we assume that the aggregator is a Cobb-Douglas function. In the computational model, we assume the aggregator is a more realistic CES function. The results are very similar to the theoretical model.

subsidies on the environment in isolation of other channels by which free trade agreements affect the environment. The total effect of the free trade agreement on the environment will be the combination of all of these channels. Let primes denote next period's value, and  $\delta$  the depreciation rate, then the aggregate resource constraint is:

$$Y_C = C + K' - (1 - \delta) K. \quad (2.13)$$

Households use an efficient mix of  $X_D$  and  $M$  to form the aggregate good. Let  $p_c$  denote the price of the aggregate good,  $p_D$  denote the price of the good produced domestically, and  $p_w(1 + \tau_D)$  denote the domestic price of the imported good, where  $\tau_D$  is a tariff and  $p_w$  is the world price, normalized to one. Hence,  $p_c$  and  $p_D$  are the price of the aggregate and domestic good in terms of world goods, respectively.

Optimality requires the marginal contribution of the inputs of the aggregate good equal their prices:

$$\mu p_c X_D^{\mu-1} M^{1-\mu} = p_D, \quad (2.14)$$

$$(1 - \mu) p_c X_D^\mu M^{-\mu} = 1 + \tau_D. \quad (2.15)$$

Hence the marginal rate of technical substitution equals the price ratio:

$$\frac{1 - \mu}{\mu} \frac{X_D}{M} = \frac{1 + \tau_D}{p_D}. \quad (2.16)$$

### 2.2.2 Trade

We assume an exogenous foreign demand curve for domestically produced goods. Let  $\tau_F$  denote the world tariff on domestic production, then:

$$X_F = \hat{D} (p_D (1 + \tau_F))^{\frac{-1}{1-\zeta}}. \quad (2.17)$$

Here  $\frac{-\mu}{1-\mu} < \zeta < 1$ . If foreigners also use a Cobb-Douglas Armington aggregator, the elasticity of substitution is one or  $\zeta = 0$ . Let  $D \equiv \hat{D} (1 + \tau_F)^{\frac{-1}{1-\zeta}}$ , then:

$$X_F = D p_D^{\frac{-1}{1-\zeta}}. \quad (2.18)$$

In this section we assume capital markets are closed.<sup>15</sup> Since capital markets are closed,

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<sup>15</sup>We allowed capital markets to open in the computational model, and the results did not change much.

trade in goods must balance:

$$M = p_D X_F. \quad (2.19)$$

### 2.3 Government

The government budget is balanced by including a lump sum transfer,  $TR$ . Thus the government budget constraint sets interest plus direct subsidies equal to lump sum taxes plus tariff revenue  $TF \equiv \tau_D M$ :

$$srK_G + S = -TR + TF. \quad (2.20)$$

It is straightforward to show that the direct subsidies equal total wage payments less the total product of labor, that is, direct subsidies equal the total cost of the hiring constraint. Hence:

$$srK_G + (w - A_G F_h(K_G, l_G)) l_G = -TR + TF. \quad (2.21)$$

### 2.4 Market Clearing

Market clearing requires demand for domestic goods to equal domestic production,  $Y$ :

$$X_D + X_F = Y. \quad (2.22)$$

Further, domestic production must equal income from factor payments plus transfers:

$$Y = \frac{1}{p_D} (rK + w + TR). \quad (2.23)$$

### 2.5 Pollution

We assume emissions of a flow pollutant,  $P$ , is proportional to domestic production. Let  $\sigma$  denote the emissions intensity of output. Then:

$$P = \sigma_G Y_G + \sigma_P Y_P. \quad (2.24)$$

Here  $Y_G$  and  $Y_P$  are subsidized and private production, respectively. No abatement technology exists, so pollution falls only by reducing output or by moving production to the less pollution intensive sector.<sup>16</sup> Given that the private and subsidized sectors are at different

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<sup>16</sup>We do not include abatement as we wish to focus on the direct effect of subsidies on pollution. Including an abatement technology such that optimal abatement increases with income would strengthen our results.

technology levels, it is reasonable to assume that they also have different pollution intensities. We can write total pollution as a fraction of total output in the following way:

$$P = \sigma Y, \quad (2.25)$$

where  $Y$  is total output and  $\sigma$  is the economy wide emissions intensity:

$$\sigma \equiv \frac{\sigma_G Y_G + \sigma_P Y_P}{Y}, \quad Y \equiv Y_G + Y_P. \quad (2.26)$$

### 3 Theoretical Results

To characterize the equilibrium, we substitute out for the firm and trade variables so as to write the model as a single capital accumulation problem. Equations (2.16), (2.18), and (2.19) imply the domestic demand curve is:

$$X_D = \frac{\mu}{1 - \mu} D (1 + \tau_D) p_D^{\frac{-1}{1-\zeta}}. \quad (3.1)$$

To find the domestic price, we can substitute the foreign demand curve (2.18) and the domestic demand curve (3.1) into the market clearing condition (2.22), to get:

$$p_D = \left( \frac{D}{(1 - \psi) Y} \right)^{1-\zeta}, \quad \psi \equiv \frac{\mu(1 + \tau_D)}{1 + \mu\tau_D}. \quad (3.2)$$

Hence:

$$X_D = \psi Y, \quad (3.3)$$

$$X_F = (1 - \psi) Y, \quad (3.4)$$

$$M = D^{1-\zeta} ((1 - \psi) Y)^\zeta. \quad (3.5)$$

Note that  $\psi$  is the share of domestic output consumed domestically, with  $\psi = \mu$  if  $\tau_D = 0$ . Finally, substituting the demand functions into the aggregate resource constraint implies:

$$C + K' - (1 - \delta) K = \Omega Y^\phi, \quad (3.6)$$

$$\Omega \equiv \psi^\mu (1 - \psi)^{\zeta(1-\mu)} D^{(1-\mu)(1-\zeta)}, \quad (3.7)$$

$$\phi \equiv \mu + \zeta(1 - \mu). \quad (3.8)$$

Here  $\phi = \mu$  and  $\Omega = \psi^\mu D^{(1-\mu)}$  if foreigners use a Cobb-Douglas Armington Aggregator. The resource constraint (3.6) shows how foreign demand affects resources available for aggregate consumption or investment. Note that under our maintained assumptions,  $\phi \in (0, 1)$ .

Let  $k$  denote the capital stock of an individual, then the recursive household problem is:

$$v(k, K) = \max_{k'} \left\{ u \left[ \Omega(r(K; s; l_G)k + w(K; s; l_G) + TR(K; s; l_G))^\phi - k' + (1 - \delta)k \right] + \beta v(k', K') \right\}. \quad (3.9)$$

We characterize the model by establishing the existence and properties of the equilibrium.

**Definition 1** *A Recursive Competitive Equilibrium given individual and aggregate capital stocks  $k$  and  $K$  and government policies  $\{\tau_F, \tau_D, s, l_G\}$  is a set of individual household decisions  $\{c, k'\}$ , trade decisions  $\{X_D, X_F, M\}$ , prices  $\{r, w, p_D, p_c\}$ , aggregate household decisions  $\{C, K'\}$ , a subsidized firm input decision  $K_G$ , private firm input decisions  $\{K_P, l_P\}$ , government variables  $\{S, TR\}$ , and a value function  $v$  such that the household's and producers' (private and subsidized) problems are satisfied, all markets clear, subsidized firms earn zero profits, the government budget constraint is satisfied, and the consistency conditions ( $k = K$  implies  $c = C$  and  $k' = K'$ ) are satisfied.*

Capital accumulation is then determined from the equilibrium first order condition and envelope equation:

$$u_c(C(K; s; l_G)) = \beta v_k(K', K') \quad (3.10)$$

$$v_k(K, K) = u_c(C(K; s; l_G)) \left( \phi \Omega Y(K; s; l_G)^{\phi-1} r(K; s; l_G) + 1 - \delta \right) \quad (3.11)$$

$$C(K; s; l_G) = \Omega Y(K; s; l_G)^\phi - K' + (1 - \delta)K \quad (3.12)$$

$$Y(K; s; l_G) = A_P F(K - K_G(K; s; l_G), 1 - l_G) + A_G F(K_G(K; s; l_G), l_G) \quad (3.13)$$

Our strategy is to establish some basic properties of the competitive equilibrium, and then use these properties to derive the more complicated results on how pollution changes with changes in subsidies.

**THEOREM 1** *Suppose  $u$  and  $F$  are as described above. Then a competitive equilibrium*

exists. Further, the equilibrium gross investment function  $K' = H(K)$  is such that:

1.  $H_K(K) \geq 0$ ,
2.  $C_K(K) \geq 0$ ,
3.  $H(K)$  satisfies the Euler equation derived from (3.10) and (3.11), and
4.  $H(K)$  is concave.

All proofs are in the Appendix.

A trade agreement often consists of a combination of reductions in tariffs and subsidies to domestic enterprises. In order to derive intuition on the effect of each type of government subsidy, we consider each one in isolation. In particular, we consider a reduction in interest subsidies leaving the labor requirement unchanged (notice that this increases the losses made by subsidized firms and, thus, the direct subsidies), a reduction in direct subsidies, where the labor requirement is reduced so that interest subsidies are kept constant, and a reduction in world tariffs.

### 3.1 The Effect of Reducing Interest Subsidies

Consider first a reduction in the interest subsidy rate to firms, holding the labor requirement fixed. According to the industrial structure described above, direct subsidies must rise so that subsidized firms continue to earn zero profits. Differentiating the pollution accumulation equation (2.24) with respect to  $s$  gives:

$$\frac{\partial P}{\partial s} = \sigma_G \left( A_G F_k(K_G, l_G) \frac{\partial K_G}{\partial s} \right) - \sigma_P \left( A_P F_k(K - K_G, 1 - l_G) \frac{\partial K_G}{\partial s} \right). \quad (3.14)$$

Equation (2.10) implies the after-subsidy marginal products are equal. Hence:

$$= (\sigma_G(1 - s) - \sigma_P) r(K) \frac{\partial K_G}{\partial s}. \quad (3.15)$$

Equation (2.7) implies current period pollution is increasing in the subsidy if and only if:

$$\frac{\sigma_G}{\sigma_P} > \frac{1}{1 - s}. \quad (3.16)$$

From equation (3.14), a decrease in the interest subsidy causes capital to flow from the more pollution intensive government sector to the less pollution intensive private sector, reducing pollution. However, due to the subsidy the private sector has a higher marginal product of capital, so output rises as capital flows to the private sector. It follows that for overall

pollution emissions to fall, the ratio of emissions intensities must be greater than the ratio of marginal products, which equals  $\frac{1}{1-s}$ . Changes in the lump sum direct subsidy do not affect the equilibrium allocations.

In addition to the static effect, a decrease in interest subsidies has a dynamic effect on pollution through changes in the path of capital accumulation.

**THEOREM 2** *Let  $F$  and  $u$  be as described above,  $\sigma_G > \sigma_P$ , and suppose a decrease in  $s$  holding  $l_G$  fixed. Let  $K_0 = \bar{K}$ . Then:*

1. *The economy transitions to a new steady state  $(\bar{\bar{K}}, \bar{\bar{P}})$  with lower pollution ( $\bar{\bar{P}} < \bar{P}$ ) and capital ( $\bar{\bar{K}} < \bar{K}$ ).*

*If condition (3.16) holds, then in addition:*

2. *Investment falls:  $\frac{\partial K_{t+1}}{\partial s} > 0 \forall t \geq 0$  and*
3. *pollution falls:  $\frac{\partial P_t}{\partial s} > 0 \forall t \geq 0$ .*

As shown above, if subsidized firms are sufficiently more pollution intensive, the capital reallocation resulting from a decrease in the interest subsidy causes current pollution to fall. This is the capital resource reallocation effect described above. In addition, the reduction in interest subsidies lowers the overall return to capital, causing investment to fall. Since pollution is an increasing function of output, future pollution and steady state pollution fall as well. This is the capital accumulation effect discussed above. Because the capital accumulation effect causes pollution to fall with subsidies regardless of pollution intensity, the condition needed for steady state pollution to decrease with a reduction in subsidies is weaker. That is, if (3.16) is not satisfied but  $\sigma_G > \sigma_P$ , then, following a decrease in interest subsidies, initially pollution rises but subsequently falls to a lower steady state.

It is straightforward to interpret the capital reallocation effect in terms of the familiar scale and technique effects. From equation (2.25):

$$\frac{\partial P}{\partial s} = \frac{\partial \sigma}{\partial s} Y + \sigma \frac{\partial Y}{\partial s}. \quad (3.17)$$

After simplifying, we obtain:

$$\frac{\partial P}{\partial s} = (\sigma_G - \sigma_P) \frac{\partial K_G r(K) \left( (1-s) Y^P + Y^G \right)}{\partial s Y} - s \sigma \frac{\partial K_G r(K)}{\partial s}. \quad (3.18)$$

Hence the technique term is positive for  $\sigma_G > \sigma_P$  and the scale term is negative. Therefore, a decrease in the interest subsidy rate reduces current pollution through a technique effect

and increases current pollution through a scale effect. Given condition (3.16), the technique effect dominates and a reduction in the subsidy rate causes pollution to fall. Reducing the interest subsidy lowers steady state output, since the increase in productivity is more than offset by the fall in steady state capital. Hence both the technique and scale effects cause steady state pollution to fall with subsidies, for  $\sigma_G > \sigma_P$ .

### 3.2 The Effect of Reducing Direct Subsidies

Next we consider a reduction in direct subsidies, holding the interest subsidy rate fixed. With  $s$  fixed, if subsidized firms are to earn zero profits direct subsidies can be reduced only by reducing the labor requirement. The following theorem shows that under a stronger condition, reducing direct subsidies causes pollution to fall.

**THEOREM 3** *Let  $F$  and  $u$  be as described above and suppose a decrease in  $l_G$  holding  $s$  fixed. Let  $K_0 = \bar{K}$ . Let:*

$$\frac{\sigma_G}{\sigma_P} > \max \left\{ \frac{w(K_t)}{A_G F_l(K_G(K_t), l_G)}, \frac{1}{1-s} \right\} \forall t \geq 0. \quad (3.19)$$

*Then:*

1. *pollution falls below  $\bar{P}$  for all  $t \geq 0$ , and*
2. *for periods  $t > 1$ , pollution transitions monotonically to a new steady state  $\bar{\bar{P}} < \bar{P}$ .*

In the initial period the labor requirement decreases to offset the reduction in direct subsidies causing a labor reallocation effect. As labor moves from subsidized to private firms it becomes more productive (from  $A_G F_l$  to  $w$ ), which tends to increase output and therefore pollution. However, since private firms are less pollution intensive, pollution tends to fall when labor moves from subsidized to private firms. Condition (3.19) requires the latter of these two effects to be stronger. Capital also moves to the private sector, so we have a capital reallocation effect and condition (3.16) is also needed for pollution to fall. The intuition for (3.19) is identical to the intuition for (3.16): both imply the reallocation of resources to the private sector causes a decrease in pollution intensity that outweighs the increase in output.

After the initial fall in pollution, the labor requirement does not change, but a capital accumulation effect exists, as capital converges to a new steady state. The behavior of pollution in the transition to the new steady state depends on whether condition (2.6) holds. If condition (2.6) does not hold, then capital declines monotonically to a new steady state and  $\frac{1}{1-s}$  is larger than the wage ratio. Thus given condition (3.16) and not (2.6), pollution declines monotonically to a new steady state below the initial drop in pollution.

If condition (2.6) holds, then steady state capital may rise or fall after the reduction in the labor requirement and the wage ratio is larger than  $\frac{1}{1-s}$ . If steady state capital declines, pollution falls further over time. If capital rises then pollution rises over time, but not by enough to offset the initial fall in pollution. Figure (1) illustrates the possible time paths of pollution.

For Cobb-Douglas production with labor share  $1-\alpha$ , the wage ratio in (3.19) is a function of only parameters:

$$\frac{w(K_t)}{A_G F_l(K_G(K_t), l_G)} = \left( \frac{A_P (1-s)^\alpha}{A_G} \right)^{\frac{1}{1-\alpha}}. \quad (3.20)$$

In the calibration,  $A_G$  turns out to be large enough so that  $\frac{1}{1-s}$  is larger than the wage ratio and thus conditions (3.19) and (3.16) are identical.

Notice that if condition (3.19) is satisfied, then a trade agreement which reduces both direct and interest subsidies (and therefore relaxes the labor requirement), also reduces pollution.

As in the previous section, we can break down the effect of direct subsidies on pollution into a positive technique term and a negative scale term. Thus condition (3.19) is a sufficient condition for the technique effect to dominate, so that a reduction in direct subsidies reduces current pollution.

### 3.3 The Effect of Reducing Tariffs

In the third experiment, we suppose a trade treaty requires the world to lower tariffs on the exported good. Equation (2.18) implies that this is equivalent to a shift of the world demand curve for the exported good, which increases  $\Omega$ .

The effect on pollution of a trade treaty which lowers world tariffs is then:

**THEOREM 4** *Let  $F$  and  $u$  be as described above and suppose an increase in  $\Omega$  holding  $l_G$  and  $s$  fixed. Let  $K_0 = \bar{K}$ . Then:*

1. *There is no effect on current pollution,*
2. *investment rises,*
3. *pollution rises for  $t \geq 1$ ,*
4. *The economy transitions to a new steady state  $(\bar{\bar{K}}, \bar{\bar{P}})$  with higher pollution  $(\bar{\bar{P}} > \bar{P})$  and capital  $(\bar{\bar{K}} > \bar{K})$ .*

Note that if  $\zeta(1 + \tau_D) < 1$  (satisfied if  $\zeta = 0$ ), then an increase in domestic tariffs also increases  $\Omega$  and pollution. If both foreign and domestic tariffs fall in a trade treaty, then the effect on  $\Omega$  and therefore pollution depends on the size of the preexisting tariffs.

The increase in foreign demand that follows a reduction of the world trade barriers improves the return to capital and increases investment, which in turn results in the creation of more pollution-causing factories.

No technique effect exists here, the only effect of a change in world tariffs is the effect on capital accumulation. In this sense, our results differ from Antweiler, Copeland, and Taylor (2001), who find a technique effect due to lowering trade barriers. Their technique effect is driven by abatement policy, which is constant in our model. Furthermore, we have ruled out the PHH and the factor endowment hypothesis by assumption.

Hence a trade treaty that reduces subsidies as well as tariffs has an ambiguous effect on pollution. However, we argue here (and show in the simulations for the case of China) that overall pollution is likely to fall if (3.19) holds. The reason is that first both foreign and domestic tariffs generally fall, so the effect on  $\Omega$  is ambiguous. But even if  $\Omega$  rises, the trade treaty has an ambiguous scale effect on pollution causing-capital accumulation (interest subsidies fall but the return to capital increases with foreign demand), but an unambiguous technique effect on pollution, caused by capital flowing to the less pollution intensive private sector.

## 4 Computational Model

### 4.1 Extended Model

In this section we use a dynamic applied general equilibrium model in order to assess the quantitative effects of changes in tariffs and subsidies associated with China's accession to the WTO on pollution emissions. In order to make quantitative predictions, the computational model adds several features not present in the theoretical model.<sup>17</sup> In particular, the computational model considers two final goods, a traded good and a non-traded good. Due to data availability, we assume that the pollution intensity of the private and the state sector do not vary across final goods. Some other extra features of the computational model include capital adjustment costs and taxes on output. The model also features exogenous technological change in both TFP and pollution intensity.

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<sup>17</sup>None of these features are critical for our qualitative analysis of the effect of subsidies to the state sector on pollution and, therefore, the intuition from the simplified model applies to the quantitative model.

The representative individual solves the following problem:

$$\begin{aligned}
\max \quad & \sum_{t=0}^{\infty} \beta^t (\epsilon c_{1t}^\rho + (1 - \epsilon) c_{2t}^\rho - 1) \frac{1}{\rho} \\
\text{s.t.} \quad & p_{1t} c_{1t} + p_{2t} c_{2t} + a_{t+1} = w_t + (1 + r_t) a_t + TR_t \\
& a_t \geq -A \\
& a_t = q_{P1t-1} k_{P1t} + q_{P2t-1} k_{P2t} + q_{G1t-1} k_{G1t} + q_{G2t-1} k_{G2t} \\
& k_{P10}, k_{P20}, k_{G10}, k_{G20} \text{ given}
\end{aligned} \tag{4.1}$$

where  $c_{1t}$  and  $c_{2t}$  are consumption of the traded and non-traded goods, respectively,  $p_{it}$  is the price of good  $i$ , and  $a_t$  represents the assets held by the individual. Consumers hold capital in each sector and industry,  $k_{ijt}$ . Here  $q_{ijt-1}$  is the return at period  $t$  of capital of type  $ij$  invested at  $t - 1$  to be used in period  $t$ . Adjustment costs make capital sector and industry dependent.

Production  $Y$  of sector  $i$  in industry  $j$  is:

$$Y_{ij} = \min \left\{ \frac{Z_{ij1}}{v_{j1}}, \frac{Z_{ij2}}{v_{j2}}, A_{ij} K_{ij}^{\alpha_j} l_{ij}^{1-\alpha_j} \right\}, \quad i = P, G \quad j = 1, 2. \tag{4.2}$$

Here  $Z_{ijk}$  is the use of good  $k$  in the production of good  $j$  by sector  $i$ ,  $v_{jk}$  is the quantity of good  $k$  needed to produce one unit of good  $j$ ,  $Y_{Pj} + Y_{Gj} = Y_j$ , and  $A_{ij}$  is TFP, which grows exogenously at rate  $(1 + \gamma)^{1-\alpha_j} - 1$ . The production function is thus Leontief relative to both the traded and non-traded goods, and Cobb-Douglas with respect to the capital and labor inputs. This choice of production function, standard in the literature of applied general equilibrium models, simplifies the calibration of the parameters from the input-output tables.

The Armington aggregator in the tradeable sector is CES:

$$Y_{C1} = E \left( \mu X_D^\zeta + (1 - \mu) M^\zeta \right)^{\frac{1}{\zeta}}. \tag{4.3}$$

Here  $\frac{1}{1-\zeta}$  is the elasticity of substitution between the domestic and foreign produced traded goods,  $E$  is a technology parameter, and  $Y_{C2} = Y_2$ .

Investment goods,  $I$ , are produced using the traded and non-traded goods as inputs:

$$I = A_I Z_{I1}^\nu Z_{I2}^{1-\nu}. \tag{4.4}$$

Here,  $Z_{Ij}$  represents the quantity of good  $j$  used as an intermediate input in the investment sector. The investment good can be used in either sector to increase the sector's capital stock. Since the change in pollution is sensitive to changes in capital stock across sectors and over time, it is important to have a realistic model of capital adjustment. Therefore,

following Lucas and Prescott (1971), we model sectoral and temporal adjustment costs as:

$$K'_{ij} = AC\left(\frac{I_{ij}}{K_{ij}}\right) K_{ij} + (1 - \delta) K_{ij}. \quad (4.5)$$

Here  $AC$  is the adjustment function which satisfies:

$$AC\left(\frac{I}{K}\right) \equiv \left( (\gamma - 1 + \delta)^{1-\theta} \left(\frac{I}{K}\right)^\theta - (1 - \theta)(\gamma - 1 + \delta) \right) \frac{1}{\theta}, \quad 0 < \theta \leq 1. \quad (4.6)$$

The government obtains revenue from taxes on producers of final goods,  $T$ , and from tariff revenue,  $TF$ . The tax rates  $t_j$  and the tariff rate  $\tau_D$  are exogenously given. The government purchases per capita,  $G_j$ , are also exogenous. The government budget constraint is thus:

$$p_1 G_1 + p_2 G_2 + s \sum_j r K_{Gj} + S + TR = TF + T. \quad (4.7)$$

Here tax revenues are:

$$T = \sum_{i,j} p_j t_j Y_{ij}, \quad (4.8)$$

and tariff revenues are as in Section 2.3. The government budget constraint is balanced with the lump sum transfer. Thus, for example, reductions in the subsidy rate raise lump sum transfers.

For trade, foreign demand is again given by (2.17), where  $\hat{D}$  now grows exogenously at rate  $\gamma$ , which is consistent with the existence of a balanced growth path for the model economy. Note that we are assuming foreign and domestic households have the same elasticity of substitution between foreign and domestic goods.

All markets clear, trade balances (equation 2.19 holds), and domestic and foreign demand for the traded good must equal supply (equation 2.22 holds for good one). The domestic markets for the non-traded good and the composite good also clear:

$$G_j + C_j + Z_{Ij} + \sum_{i,k} Z_{ikj} = Y_{Cj}. \quad (4.9)$$

Exogenous improvements in emissions intensity,  $\frac{1}{EI}$ , slow the growth of pollution emissions:

$$P = \sum_i \sigma_i \frac{Y_{1i}}{EI}. \quad (4.10)$$

Here  $EI$  grows exogenously at rate  $\gamma$ , which is consistent with a stationary level of pollution emissions.

## 4.2 Data and Calibration

We take the main economic parameters from Bajona and Chu (2005), who calibrate in order to match data on the Chinese National Income and Product Accounts, the Chinese input-output matrix, and the share of SOEs in Chinese industry for 1997. The values of the calibrated parameters are reported in Table 1.

To map the assumptions of the model to the Chinese economy, note that rather than exclusively privatizing SOEs, China also has allowed a private sector to arise to compete with SOEs. Further, China has given managers at SOEs performance incentives consistent with profit maximization (Choe and Yin 2000). Our assumption that households own capital is consistent with China in that households make deposits at state owned banks, who can then subsidize capital rental by SOEs.

Specific to this paper is the calibration of the pollution intensity parameters. We use the results of Wang and Jin (2002), who conducted a survey of pollution emissions of 905 industrial firms in China in 1999. They report the average pollution intensity of output,  $\sigma$ , for four flow pollutants: total suspended solids (TSS), chemical oxygen demand (COD), sulfur dioxide (SO<sub>2</sub>), and total suspended particles (TSP). Wang and Jin (2002) report pollution emissions by type of ownership: SOEs, collective owned enterprises (COEs), Private, foreign, and joint ventures. We categorize SOEs as subsidized firms and all other types of ownership as private.<sup>18</sup> The pollution intensity of private firms equals the total pollution emissions divided by the total output of the four sectors. The parameters are reported in Table 2. Unfortunately, the survey was done in 1999, so our assumption is that pollution intensity by sector did not significantly change between 1997 and 1999.

## 5 Simulation Results

The numerical experiment is to quantitatively assess the effects on pollution emissions derived from changes in subsidies to SOEs required for China's accession to the WTO. The initial year for each simulation is 1997. China has been reforming its economy at least since the early 1980s, to improve economic performance and comply with trade rules and agreements. Since it is not clear which subsidies are reduced for what reason, we focus instead on subsidies specifically targeted for elimination in the US-China WTO Bilateral Agreement (White House 1999). The agreement, signed in 1999, gives a timetable for elimination of subsidies

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<sup>18</sup>Ideally, firms should be categorized according to whether or not they receive subsidies. This data is not available. However, we view our assumption that only SOEs get subsidies as conservative. For example, COEs are more pollution intensive than private firms, and probably receive some subsidies. Finally, we do not want to use studies which compare intensity of SOEs before and after privatization, as the subsidies are likely to be (at least in the short run) similar.

of 0 to 15 years, depending on the good. We chose a five year reform period (2000-04) since most goods have a five year timetable.

Although the policy changes are not fully implemented until 2004, households change decisions beginning in 1997, in anticipation of the new policies. Changes in investment in these early years is especially complicated. For example, suppose households know the interest subsidy rate and therefore the future return to capital are to fall. Because of adjustment costs, capital created from current investment cannot be costlessly transformed into consumption when the policy takes effect. Therefore, the return to current investment falls. However, the incentive to reduce current investment is mitigated by household desire for smooth consumption. Since households know future wealth and consumption will fall, an incentive to reduce current consumption and increase current investment exists. Since pollution is proportional to output, pollution also changes in anticipation of the new policy in complicated ways. Our results therefore give caution to static empirical work in this area, since pollution is likely to vary significantly along the dynamic path to the new balanced growth path.

We consider five policy experiments. The first, which we denote the benchmark economy, assumes the WTO agreement is not signed and future policies remain at their 1997 values. In the other four experiments, policies change over the five year reform period. The benchmark economy is not in a steady state in 1997. Therefore, to isolate the effects of the changes in subsidies, we present all results relative to the benchmark economy.

In the second experiment, the labor requirement is reduced by 25% so that direct subsidies fall by 25%. This experiment is most conservative in the assessment of the changes required for China to enter the WTO, as it supposes only subsidies China specifically agreed to eliminate in the WTO agreement will in fact be eliminated. Of the subsidies specifically marked for elimination in the WTO agreement, most are direct subsidies. Bajona and Chu (2005) estimate elimination of these subsidies constitutes a reduction in direct subsidies of approximately 25%. The implied reduction in the labor requirement moves labor to the private sector. The movement of labor to the private sector increases the marginal product of capital, so capital also moves to the private sector. Both of these effects raise output, eventually to 2.36% above the benchmark model. Since pollution is proportional to output, this scale effect causes pollution to rise. However, the private sector is less pollution intensive, so the movement of labor and capital to the private sector results in a technique effect which causes pollution to fall. As shown in Table 3 and Figures 2-5, pollution falls relative to the benchmark for three of four pollutants, from a small increase in TSS of 0.5% to a 22.9% decrease in SO<sub>2</sub>. This matches the prediction of Theorem 3 as shown in the last line of Table 2. Thus pollution generally falls in our most conservative experiment in which no reduction

in interest subsidies exists, and for which COEs are treated as private firms.

The third experiment shows the effect of a 10% reduction in the interest subsidy rate, holding the labor requirement fixed. Although interest subsidies are not specifically marked for elimination, they are not allowed and could be eliminated if another country brought suit, or if (as promised) China opens its banking sector. The reduction in the subsidy rate lowers the overall return to capital and causes existing capital to flow to the private sector. The resulting fall in investment lowers steady state output relative to the benchmark economy. The steady state scale effect therefore reduces pollution here. Production also moves to the less pollution intensive private sector, further reducing pollution. Thus the scale effect and technique effect both result in a decrease in steady state pollution. As shown in Table 3 and Figures 2-5, steady state emissions of all four pollutants fall relative to the benchmark, from a 0.9% fall in TSS to 27.0% fall in SO<sub>2</sub>.

The fourth experiment is a comparative static which shows the effect of a 10% reduction in the interest subsidy rate, holding direct subsidies fixed. This is achieved with a 13% reduction in the labor requirement. The fall in pollution is more moderate; output rises by only 0.01% since the lower investment is offset by labor moving to the higher TFP private sector. Nonetheless, pollution declines relative to the benchmark in all four cases.

The final experiment supposes the world reduces tariffs to zero. This causes an increase in demand for Chinese goods and a corresponding increase in output. As shown in Table 3 and Figures 2-5, pollution rises, since in this case there is no technique effect. Relative to the benchmark, TSS increase by 0.45%, COD by 0.46%, SO<sub>2</sub> by 0.49%, and TSP by 0.48%. The effect of changes in tariffs on pollution is apparently quantitatively small relative to the effect of changes in subsidies. Tariffs are small to begin with, so even eliminating tariffs does not cause large changes. In contrast, our calibration indicates that SOEs receive a 58% discount on their capital rental, so a 10% reduction in these subsidies has quantitatively large effects. Second, our model is not designed to capture any composition effects due to shifts of production between industries with different pollution intensities. Third, since there is a relatively large difference in productivity between the state owned and private sectors, moving inputs from one sector to the other has a quantitatively large effect on output and interest rates relative to the effect of a change foreign demand.

Figure 6 breaks down the change in pollution into scale and technique effects for all pollutants and all experiments. As noted earlier, the technique effect is stronger where the difference in pollution intensity is greatest, for TSP. The scale effect is positive for the reduction in direct subsidies and the reduction in world tariffs. Notice the scale effect is theoretically identical across pollutants in percentage terms since output is independent of pollution.

## 6 Conclusions

We have given theoretical sufficient conditions for which a reduction in subsidies to industry results in a decrease in pollution. Essentially, these conditions require the subsidized sector to be sufficiently more pollution intensive than the private sector. We argue SOEs or other firms receiving various government subsidies are likely to also receive another kind of subsidy: lax enforcement of pollution regulations. Indeed, for the case of China, SOEs are more pollution intensive for all four pollutants studied. Hence in our numerical section, we show that, under the most conservative assumptions, the reduction in direct subsidies to Chinese SOEs required by WTO accession reduces pollution for three of four pollutants studied. We also show that that changes in tariffs have a minimal effect on pollution relative to changes in subsidies.

Several caveats are in order. First, given that China's state owned sector comprises about 30% of industrial output, China represents an extreme case. Still, given the evidence weak enforcement of environmental regulations on SOEs in countries like India and Indonesia, and the prevalence of SOEs in developing countries, our model is very relevant for studying the environmental effects of trade agreements in developing countries. Further, given that nearly all countries give some subsidies to industry, our model has some relevance for developed economies as well. Second, subsidized firms here are competitive. Subsidized firms may have monopoly powers. If the subsidized firm is state owned, it may suffer from agency issues. Each of these firm structures may affect pollution. Finally, our model has only one traded good and may thus miss intra-sectoral effects of lowering tariffs, as well as any effect due to shifts in production from one industry to another driven by comparative advantages (composition effects).<sup>19</sup>

The exogenous subsidies considered here are the outcome of the political process. Modeling this process is a subject of future research. Regardless of the political process, a free trade agreement, by creating new winners and losers, has the possibility of altering the political equilibrium. The trade agreement thus can potentially reduce pollution-causing subsidies in a way that a privatization may not. If the political equilibrium is unchanged, privatization is unlikely to produce significant changes.

In this paper we have found a new channel for which economic policy affects pollution, a technique effect that results when production moves from a more pollution intensive subsidized firm to a less pollution intensive private firm. This technique effect could be examined in many other contexts. For example, countries with low subsidies are both richer and have

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<sup>19</sup>For example if a particular good was pollution intensive and had high world tariffs, then the effect of tariff reductions on pollution may be more significant than what we obtain here.

a cleaner environment, thus our model would likely reproduce the environmental Kuznets curve. Our model could also be used to examine the effects of privatization on pollution. These are subjects of future research.

## 7 Appendix: Proof of theorems

### 7.1 Proof of Theorem 1

Substituting the interest rate (2.4), wage rate (2.5), and transfer (2.21) into the budget constraint for the aggregate good (3.6) and simplifying results in:

$$c + k' = G(k, K; s), \quad (7.1)$$

$$G(k, K; s) \equiv \Omega \left[ Y(K; s) + A_P F_k(K - K_G(K; s), 1 - l_G)(k - K) \right]^\phi + (1 - \delta)k, \quad (7.2)$$

$$Y(K; s) \equiv A_P F(K - K_G(K; s), 1 - l_G) + A_G F(K_G(K; s), l_G). \quad (7.3)$$

The model is now in the framework of Greenwood and Huffman (1995). By repeatedly appealing to (2.10), and the properties of the interest rate (2.8) and the share of capital in the subsidized sector (2.7), we can verify assumptions (i)-(iii) of Greenwood and Huffman. It follows from their proposition on page 615 that an equilibrium exists.

Further, equation (3) of Greenwood and Huffman states that the equilibrium investment function  $H$  is the fixed point of a recursive non-linear functional equation. The fixed point of this equation is the Euler equation. Hence  $H$  satisfies the Euler equation.

Equation (4) of Greenwood and Huffman states that  $H$  has the following properties:

$$0 \leq H_K(K) \leq G_1(K, K) + G_2(K, K), \quad (7.4)$$

$$0 < H(K) < G(K, K). \quad (7.5)$$

Equation (7.4) implies that  $c(K)$  is increasing in  $K$ . Thus since  $u$  is concave, for all  $K, K'$ :

$$(u_c(c(K)) - u_c(c(K')))(K - K') \leq 0. \quad (7.6)$$

Substituting in the Euler equation, we see that  $K' > K$  if and only if  $K < \bar{K}$ . Thus  $H$  is concave. Thus  $H$  has the properties stated in Theorem 1.

## 7.2 Proof of Theorem 2

As shown in the text, condition (3.16) implies a decrease in the subsidy decreases pollution.

For the steady state, let  $\beta = \frac{1}{1+\lambda}$ , where  $\lambda$  is the rate of time preference. Evaluating equations (3.10) and (3.11) at the steady state  $\bar{K}$  yields the modified golden rule:

$$\lambda = \phi\Omega Y(\bar{K}; s)^{\phi-1} r(\bar{K}; s) - \delta \quad (7.7)$$

Now since steady state income,  $Y(\bar{K}; s)$  is decreasing in the subsidy,  $\phi < 1$ , and  $r(\bar{K}; s)$  is increasing in the subsidy, the right hand side is increasing in the subsidy. Further, since  $Y(\bar{K}; s)$  is increasing in  $\bar{K}$ ,  $\phi < 1$ , and  $r(\bar{K}; s)$  is decreasing in  $\bar{K}$ , the right hand side is decreasing in  $\bar{K}$ . Hence a decrease in the subsidy implies a decrease in  $\bar{K}$ . It is straightforward, but tedious, to verify that  $\bar{P}$  is increasing in  $s$  given  $\sigma_G > \sigma_P$ , using (7.7).

For periods between 0 and the steady state, note that from Theorem 1,  $H(K)$  is strictly increasing and concave in  $K$ . Hence,  $K$  will converge monotonically to  $\bar{K}$  from above, since  $K_0 > \bar{K}$ . Given that pollution is increasing in the capital stock, pollution will also converge monotonically from above to  $\bar{P}$ .

## 7.3 Proof of Theorem 3

Differentiating pollution with respect to  $l_G$ , holding  $K$  fixed, we see that current pollution falls given condition (3.19). In addition, differentiating the steady state pollution with respect to  $l_G$  implies that steady state pollution falls given condition (3.19). Let  $P_0 < \bar{P}$  denote the new pollution emissions in the initial period.

For periods between 0 and the steady state, if capital is increasing, then pollution will increase monotonically to the new steady state  $P_0 < \bar{P} < \bar{P}$ . If capital is decreasing, then pollution will decline to the new steady state  $\bar{P} < P_0$ . The reasoning is identical to Theorem 2.

## 7.4 Proof of Theorem 4

Current pollution is a function of only the current capital stock, tax rates, and  $l_G$ , all of which are given. Hence current pollution is independent of  $\Omega$ . For the steady state, note that modified golden rule (7.7) for this economy implies that if  $\Omega$  rises then so does steady state capital. Since steady state pollution is increasing in the steady state capital stock for  $\sigma_G > \sigma_P$ , steady state pollution rises.

For periods between 0 and the steady state, capital and pollution will increase monotonically to the new steady state, using identical reasoning as in Theorem 2.

## 8 Appendix: Tables and Figures

Parameter	Symbol	Value		Matches:
Production Parameters		Traded	Non-Traded	
Capital Share	$\alpha$	0.24	0.38	(a)
Productivity, Private Sector	$A_{Pj,0}$	5.29	2.97	(a)
Productivity, SOEs	$A_{Gj,0}$	2.45	2.65	(a)
Unit Cost, traded	$v_{1j}$	0.54	0.11	Input-Output Tables (I/O)
Unit Cost, not-traded	$v_{1j}$	0.37	0.19	I/O
Growth rate, GDP	$\gamma$		0.02	US Trend
Armington Aggregator				
Technology Parameter	$E$		1.67	Equilibrium
Elasticity Parameter	$\zeta$		0.5	AGE Literature
Share Parameter	$\mu$		0.72	I/O, Equilibrium
Investment Parameters				
Capital Share	$\nu$		0.38	I/O
Productivity	$A_I$		1.94	Equilibrium
Depreciation	$\delta$		0.08	Investment Data
Adjustment Costs Parameter	$\theta$		0.9	US $I/K$ Volatility
Preference Parameters				
Discount Rate	$\beta$		0.95	One year period
Elasticity Parameter	$\rho$		-1.00	within RBC range
Share of traded good	$\epsilon$		0.87	I/O
Foreign Demand	$\hat{D}_0$		0.44	I/O
Policy Parameters		Traded	Non-Traded	
Production Tax	$t$	0.12	0.08	(a)
Government Consumption	$G_j$	0.00	0.21	I/O
Rental rate subsidy	$s$	0.82	0.15	(a)
Labor Restriction	$l_{Gj}$	0.19	0.18	(a)
Domestic Tariff	$\tau_D$		0.02	Tiwari, et. al. (2002)
Foreign Tariff	$\tau_F$		0.05	Tiwari, et. al. (2002)
Initial Values		Traded	Non-Traded	
Initial Private Capital	$K_{Pi0}$	0.65	0.52	$K$ series
Initial Government Capital	$K_{Gi0}$	0.96	0.56	$K$ series
Foreign Borrowing	$B_0$		0.00	I/O, $K$ series

Table 1: Economic parameter values. (a): jointly calibrated to match the output and labor inputs from input-output tables (I/O), the constructed capital stock by ownership in 1997, the share of output in each industry produced by SOEs in 1997, the share of output in the traded industry produced by SOEs in 1997, the direct subsidies to GDP ratio for 1997, and the assumption of equal capital shares in the private and state sectors. Here  $j$  indexes traded and non-traded goods. The parameter values are from Bajona and Chu (2005), Table 1.

	Emissions in Tons per 10,000 Yuan			
Firm Type	TSS	COD	SO <sub>2</sub>	TSP
SOEs ( $\sigma_G$ )	2.5	21.4	3.2	0.2
Private and Other ( $\sigma_P$ )	2.00	7.29	0.08	0.02
$\sigma_G(1-s) - \sigma_P$	-0.95	1.70	1.26	0.06

Table 2: Pollution intensity of SOEs and other enterprises. Derived from Table 4 of Wang and Jin (2002). The last line uses  $s = 0.58$ , the capital-weighted average of the traded and non-traded sectors.

	Steady State as a Percent of Baseline				
Experiment	$Y$	TSS	COD	SO <sub>2</sub>	TSP
Decrease $S$ by 25%	2.4	0.5	-7.6	-22.9	-17.6
Decrease $s$ by 10%	1.2	-0.9	-9.9	-27.0	-21.0
Decrease $s$ 10%, $S$ 25%	0.01	-1.3	-6.9	-17.5	-13.8
Decrease $\tau_F$ to 0	0.4	0.4	0.5	0.5	0.5

Table 3: Results of numerical experiments.

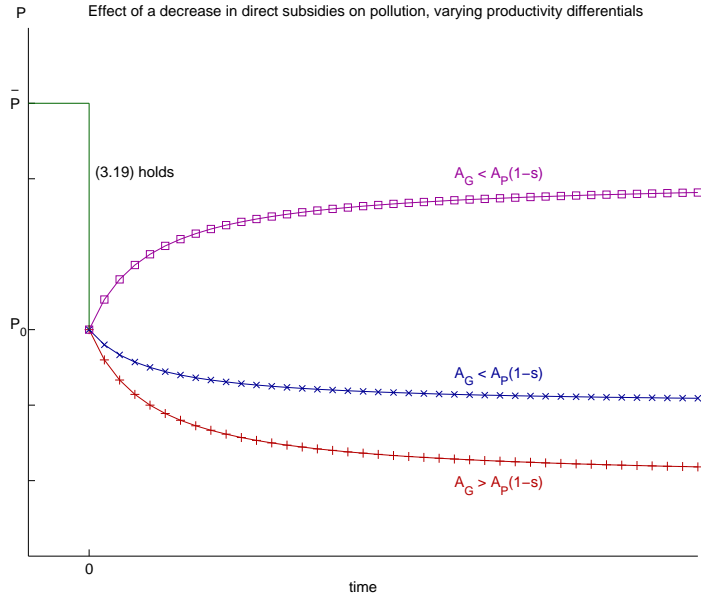


Figure 1: Changes in pollution resulting from a decrease in direct subsidies over time as a function of SOE productivity, given condition (3.19) holds.

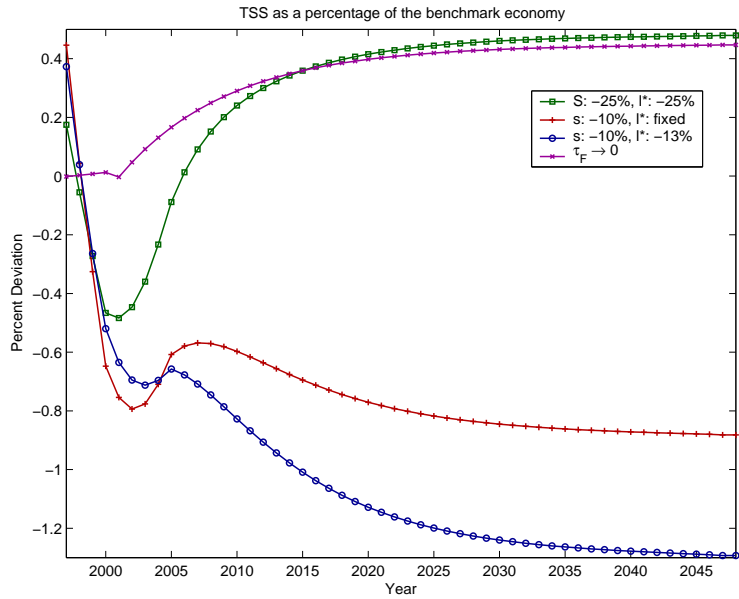


Figure 2: Total Suspended Solids relative to benchmark economy with no changes in tariffs and subsidies. Changes in tariffs and subsidies are phased in over years 2000-2004.

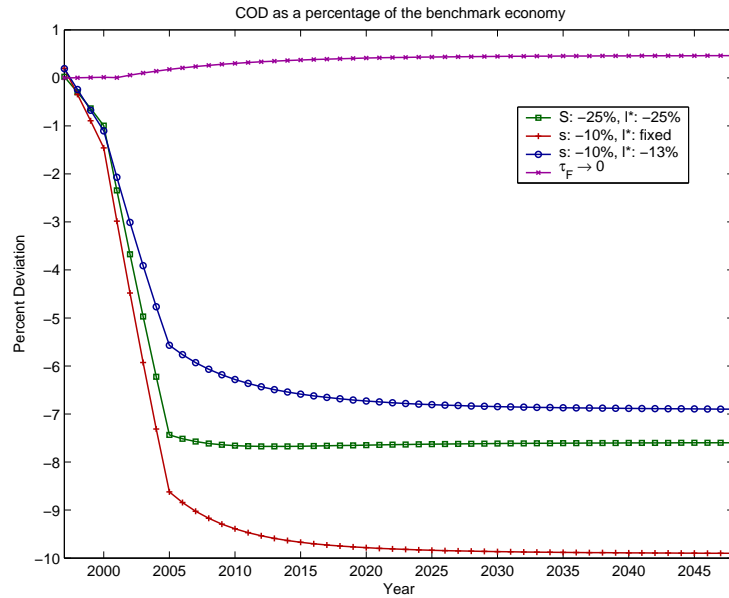


Figure 3: Chemical oxygen demand relative to benchmark economy with no changes in tariffs and subsidies. Changes in tariffs and subsidies are phased in over years 2000-2004.

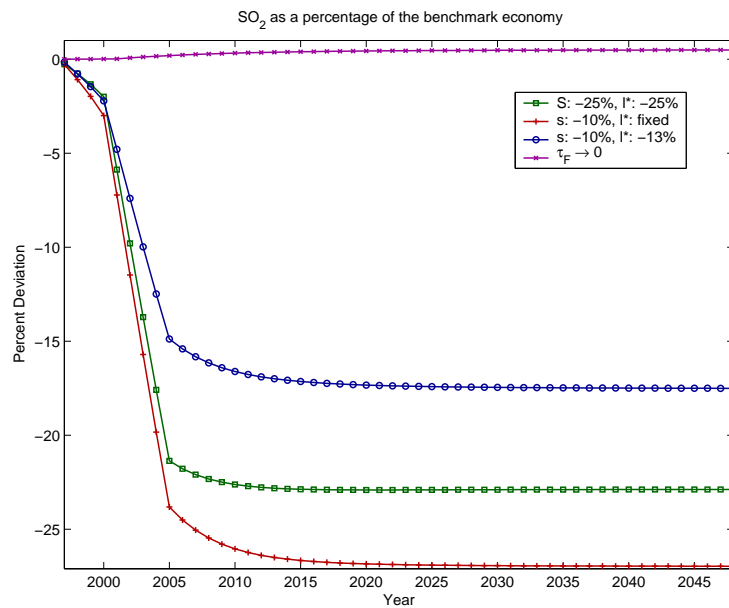


Figure 4: Sulfur Dioxide Emissions relative to benchmark economy with no changes in tariffs and subsidies. Changes in tariffs and subsidies are phased in over years 2000-2004.

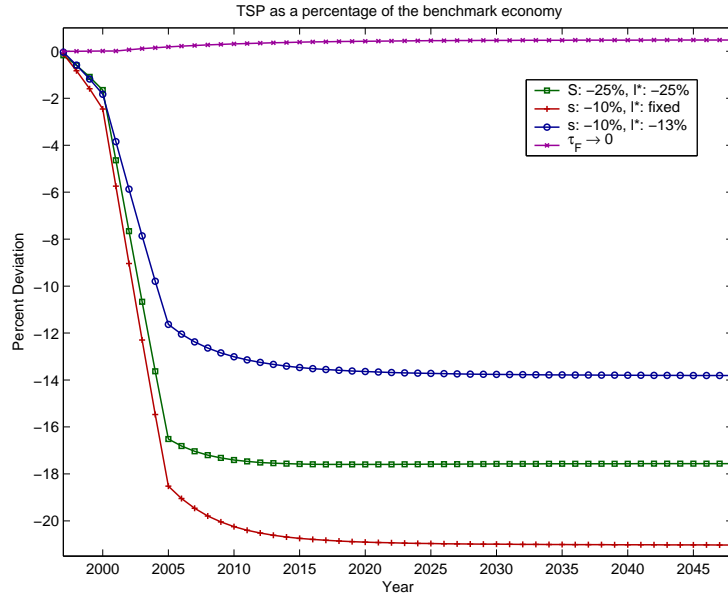


Figure 5: Total suspended particulates relative to benchmark economy with no changes in tariffs and subsidies. Changes in tariffs and subsidies are phased in over years 2000-2004.

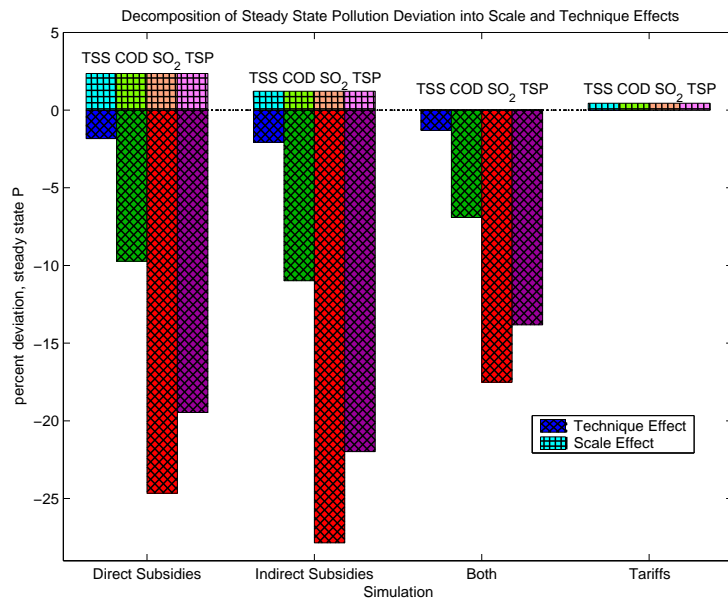


Figure 6: Decomposition of steady state change in pollution relative to the benchmark economy into scale and technique effects.

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