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 subsides 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 subsides 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 6.3% 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.[1]

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. The focus of trade agreements and this paper is not on benign and well-studied subsidies designed to correct an externality, but instead on subsidies designed solely to support a particular industry or firm (typically facing foreign competition). Such subsidies are sometimes called "perverse subsidies" (for example Myers and Kent 2001). We show that reducing such 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 subsides 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 all 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 industrial dust emissions in our model converges over time to a steady state 6.3% lower than a baseline economy in which no subsidies are reduced. Similarly, steady state chemical oxygen demand (COD) is 5% lower, sulfur dioxide (SO_2) is 3.4% lower, and soot is 2.7% lower. The reductions in pollution occurs without any environmental

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[1] Specifically, subsides 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 (2006) argue the criteria for challenging domestic subsidies in the WTO is weak enough so that governments can in principle challenge any positive subsidy.

side agreements or abatement policy changes.

There is a large theoretical literature on trade and the environment.[2] Research has 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). 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.[3] 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 affects 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 pollution 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_2 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

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[2] Survey papers include Copeland and Taylor (2004), Kolstad and Xing (1996), Rauscher (2001), and Ulph (1997).

[3] That is, we are not considering the *pollution haven effect*, which deals with the effect of environmental regulations on trade flows.

effect). They also avoid the data problems present in previous studies by using data on SO_2 pollution emissions from the Global Environmental Monitoring database. They find a particularly strong technique effect, implying that trade improves the quality of the environment by 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_2.

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.[4] 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 that economy-wide pollution intensity decreases. We reconcile these two observations by means of a shift of production from highly polluting subsidized firms to less polluting private firms, without changes to abatement policy. Our results are also 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, which they attribute to an income effect on abatement policy. We find another reason why pollution intensity may fall following a trade agreement, which helps explain the magnitude of the overall technique effect in the data.

The related literature on how perverse subsidies to industry affect the environment is less developed.[5] Since almost all countries have industrial policies which favor some industries, what effect subsidies have on the environment is an important question. Bajona and Chu (2008) 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 and subsidized firms, facing domestic and foreign competition. To receive subsidies, subsidized firms must agree to employ more labor than is efficient, which we model as a minimum labor requirement.[6] In exchange, subsidized firms receive direct (cash)

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[4] 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.

[5] 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, but note that a full assessment would require a general equilibrium analysis, which we do here. 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. Fisher-Vanden and Ho (2007) show that capital subsidies reduce the cost of adopting a carbon tax in China, since the carbon tax offsets some of the distortions caused by the capital subsidy. More established is the literature on agricultural subsidies and the environment (see for example Antle, Lekakis, and Zanias 1998).

[6] Although we take the labor requirement as exogenous, it is consistent with the idea that subsidized firms increase employment to increase bargaining power with the government (Yin 2001).

subsidies to cover the negative profits that result from the use of an inefficient mix of capital and labor.[7] Subsidized firms also receive low interest loans from the government or state owned banks, modeled as an interest rate subsidy.[8] 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 differences. Subsidies thus affect pollution by changing the share of production of the subsidized sector.

Our firm structure is somewhat related to that of Fisher-Vanden and Ho (2007). They have interest subsidies but do not separately model subsidized and non-subsidized firms. Instead, an exogenous percentage of capital in each industry is subsidized. In contrast, in our model the share of capital which is subsidized is endogenous, and both subsidized and non-subsidized firms co-exist. Thus, in their model a reduction in subsidies to a particular industry causes capital to flow to other industries, reducing pollution if other industries are less pollution intensive via a composition effect. In contrast, in our model a reduction in subsidies causes capital to move endogenously from subsidized to private firms even *within* an industry, reducing pollution if subsidized firms are more pollution intensive via a technique effect.

A related empirical literature on heavily subsidized SOEs and the environment also exists. Wang and Jin (2007) find SOEs in China are more than 50% more pollution intensive than non-SOEs. In addition, Gupta and Saksena (2002) find that SOEs in India are monitored for environmental compliance less often than private firms. Dasgupta, Laplante, Mamingi, and Wang (2001) 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 pollution intensive than private firms, even after controlling for age, size, and efficiency. Hettige, Huq, and Pargal (1996) survey studies with similar results. Galiani, Gertler, and Schargrodsky (2005) find that privatization of water services in Argentina improved health outcomes. However, Earnhart and Lizal (2006) 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.[9]

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[7] Direct subsidies can thus be thought of as “bailouts” for firms in danger of exiting the market due to negative profits.

[8] 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.

[9] 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

In our model, reducing subsidies affects pollution through two main mechanisms. The first mechanism, which we call *capital and labor resource reallocation effects*, is static in nature and is the effect of the reallocation of capital and labor from subsidized to private firms that reducing subsidies induces. First, reducing direct subsidies decreases equilibrium employment in subsidized firms, causing output to become more concentrated in private firms. Second, this decrease in employment causes capital to flow to the private sector, further concentrating output in private firms. If subsidized firms are more pollution intensive, these two effects cause pollution to decrease. However, as resources concentrate in the higher-productivity private sector, overall output and therefore pollution rises. 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, reducing subsidies to firms directly reduces overall demand for capital. On the other hand, the rise in overall productivity caused by the concentration of capital in the private sector tends to increase demand for capital. We show conditions for which the former effect is stronger so the return to capital falls with subsidies, causing the capital accumulation to slow or fall, which implies pollution grows more slowly or falls over time as well.

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 technology F and are competitive price takers.[10] 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, the government covers any losses through direct (cash) subsidies. If the labor requirement binds,

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the latter changes ownership.

[10] Some subsidized firms clearly have monopoly power. This assumption is discussed in Section 7.

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 subsidies from the government to earn zero profits.[11] Therefore, let $S = -\pi_G$ be the direct subsidy, where π_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. We assume subsidized firms take S as given, which is not restrictive since the firm cannot increase profits by taking into account that its decisions affect S. 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 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 $\hat{r}$ (in terms of world goods), the rental rate of capital for subsidized firms is $(1-s)\hat{r}$, where s is the subsidy rate. Interest subsidies can be interpreted as the government guaranteeing repayment of funds borrowed by subsidized firms or steering household deposits at state owned banks to subsidized firms at reduced interest rates or as SOEs borrowing at the government's rate of interest.[12]

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.[13] 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 for private firms is standard. Let q_D denote the world price of the domestically produced good, then:

$$\pi_P = \max_{K_P, l_P} q_D A_P F\left(K_P, l_P\right) - \hat{r} K_P - \hat{w} l_P. \tag{2.1}$$

Here K_P and K_G are the parts of the aggregate per person capital stock allocated to the private and subsidized sectors, respectively, and $K = K_G + K_P$ is the aggregate capital stock

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[11] In the absence of subsidies, in a competitive equilibrium only the firm with the highest TFP operates.

[12] The latter two interpretations are more reasonable for developing countries. All three interpretations are consistent with households renting capital.

[13] 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).

per person. Let subscripts on functions denote partial derivatives. The equilibrium rental and wage rates (in terms of domestic goods), r and w, are:

$$r = \hat{r}/q_D = A_P F_k \left(K - K_G, 1 - l_G\right), \tag{2.2}$$

$$w = \hat{w}/q_D = A_P F_l \left(K - K_G, 1 - l_G\right). \tag{2.3}$$

The problem of a subsidized firm consists of maximizing profits subject to the minimum labor constraint. The labor constraint is binding (subsidized firms hire more labor than is efficient) if and only if $\hat{w} > q_D A_G F_l \left(K_G, l_G\right)$. 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,[14] which implies:

$$\pi_G = \max_{K_G} q_D A_G F \left(K_G, l_G\right) - (1 - s)\, \hat{r} K_G - \hat{w} l_G. \tag{2.4}$$

The first order condition which determines the part of the capital stock allocated to the subsidized sector is:

$$(1 - s)\, r = A_G F_k \left(K_G, l_G\right). \tag{2.5}$$

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 (2.5), (2.2), and (2.3) have a unique solution $K_G \left(K, A_G/A_P (1 - s), l_G\right)$, $r = r\left(K, A_G/A_P (1 - s), l_G\right)$, and $w = w\left(K, A_G/A_P (1 - s), l_G\right)$.

We can also show:

$$\frac{\partial K_G}{\partial s} > 0 \ , \ \frac{\partial r}{\partial s} > 0 \ , \ \frac{\partial w}{\partial s} > 0, \tag{2.6}$$

$$0 < \frac{\partial K_G}{\partial K} < 1 \ , \ \frac{\partial r}{\partial K} < 0, \frac{\partial w}{\partial K} > 0, \tag{2.7}$$

$$\frac{\partial K_G}{\partial l_G} > 0 \ ; \ \frac{\partial r}{\partial l_G} > 0 \text{ and } \frac{\partial w}{\partial l_G} < 0 \ \Leftrightarrow \ A_P (1 - s) < A_G. \tag{2.8}$$

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

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[14] A somewhat restrictive sufficient condition for the constraint to bind is: $(1 - s) A_P > A_G$. For a Cobb-Douglas production function with capital share α, the constraint binds if and only if $(1 - s)^{\alpha} A_P > A_G$.

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 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:

$$(1-s)\, A_P F_k\left(K-K_G, 1-l_G\right) = A_G F_k\left(K_G, l_G\right). \tag{2.9}$$

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, Y, 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:

$$\max \sum_{t=0}^{\infty} \beta^t u\left(c_t\right). \tag{2.10}$$

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:[15]

$$Y_c = X_D^{\mu} M^{1-\mu}. \tag{2.11}$$

We can interpret μ 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 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 δ the depreciation rate. Then the aggregate resource constraint is:

$$Y_c = C + K' - (1-\delta) K. \tag{2.12}$$

Households use an efficient mix of X_D and M to form the aggregate good. Let q_c denote the world price of the aggregate good, and $q_w (1+\tau_D)$ denote the domestic price of the imported good, where τ_D is a tariff and q_w is the world price, normalized to one.

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

$$\mu q_c X_D^{\mu-1} M^{1-\mu} = q_D, \tag{2.13}$$

$$(1-\mu) q_c X_D^{\mu} M^{-\mu} = 1 + \tau_D. \tag{2.14}$$

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

$$\frac{1-\mu}{\mu}\frac{X_D}{M} = \frac{1+\tau_D}{q_D}. \tag{2.15}$$

2.2.2 Trade

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

$$X_F = \hat{D} \left(q_D (1+\tau_F)\right)^{\frac{-1}{1-\varsigma}}. \tag{2.16}$$

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[15] The Armington aggregator assumption is a standard assumption (see for example Fisher-Vanden and Ho 2007), which 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 qualitative results are very similar to the theoretical model's.

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

$$X_F = Dq_D^{\frac{-1}{1-\zeta}}. \tag{2.17}$$

In this section we assume capital markets are closed.[16] Since capital markets are closed, trade in goods must balance:

$$M = q_D X_F. \tag{2.18}$$

2.3 Government

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

$$s\hat{r}K_G + S = -\hat{TR} + TF. \tag{2.19}$$

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 in terms of domestic goods:

$$srK_G + \left(w - A_G F_h\left(K_G, l_G\right)\right) l_G = -TR + \frac{TF}{q_D}, \tag{2.20}$$

where $TR \equiv \hat{TR}/q_D$.

2.4 Market Clearing

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

$$X_D + X_F = Y. \tag{2.21}$$

Further, the value of domestic production plus tariff revenue must equal income from factor payments plus transfers:

$$q_c Y_c = q_D Y + TF = \hat{r}K + \hat{w} + \hat{TR}, \tag{2.22}$$

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[16] If we instead assumed a small open economy with a fixed interest rate, then the equilibrium function $K_G\left(.\right)$ is unchanged and subsidies will still cause the economy to over-accumulate capital since the demand for capital still rises. We also considered open capital markets in the computational section and the results were qualitatively unchanged.

$$Y_c = \frac{q_D}{q_c}\left(rK + w + TR\right). \tag{2.23}$$

2.5 Pollution

We assume emissions, E, of a flow pollutant is proportional to domestic production. Let Y_i denote output and σ_i denote the emissions intensity of output in sector $i \in \{G, P\}$. Then:

$$E = \sigma_G Y_G + \sigma_P Y_P. \tag{2.24}$$

No abatement technology exists, so pollution falls only by reducing output or by moving production to the less pollution intensive sector.[17] Given that the private and subsidized sectors are at different 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, Y:

$$E = \sigma Y. \tag{2.25}$$

Here σ is the economy wide pollution intensity:

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

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 (2.15), (2.17), and (2.18) imply the domestic demand curve is:

$$X_D = \frac{\mu}{1-\mu} D \left(1 + \tau_D\right) q_D^{\frac{-1}{1-\zeta}}. \tag{3.1}$$

Substitution of the foreign demand curve (2.17) and the domestic demand curve (3.1) into the market clearing condition (2.21), gives the domestic price:

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

Hence:

$$X_D = \psi Y, \tag{3.3}$$

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[17] 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.

$$X_F = (1-\psi)\,Y, \tag{3.4}$$

$$M = D^{1-\zeta}\left((1-\psi)\,Y\right)^{\zeta}, \tag{3.5}$$

$$q_c = \frac{\psi^{1-\mu}}{\mu\,(1-\psi)^{1-\zeta\mu}}\left(\frac{D}{Y}\right)^{\mu(1-\zeta)}. \tag{3.6}$$

Note that ψ is the share of domestic output consumed domestically, with $\psi = \mu$ if $\tau_D = 0$.

Finally, substituting the prices and equation (2.23) into the aggregate resource constraint implies:

$$C + K' - (1-\delta)\,K = \Omega\frac{\psi}{\mu}Y^{\phi}, \tag{3.7}$$

$$\Omega \equiv \mu\psi^{-(1-\mu)}\,(1-\psi)^{\phi-\mu}\,D^{1-\phi}, \tag{3.8}$$

$$\phi \equiv \mu + \zeta\,(1-\mu)\,. \tag{3.9}$$

Here $\phi = \mu$ and $\Omega = \mu\,(D/\psi)^{(1-\mu)}$ if foreigners use a Cobb-Douglas Armington Aggregator. The resource constraint (3.7) 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 after substituting for the prices, the recursive household problem is:

$$\begin{aligned} v\,(k,K) &= \max_{k'}\left\{u\left[\Omega\frac{\psi}{\mu}Y\,(K;s;l_G)^{\phi} + \frac{\Omega}{Y\,(K;s;l_G)^{1-\phi}}r\,(K;s;l_G)\,(k-K) + \right.\right. \\ &\left.\left. (1-\delta)\,k - k'\right] + \beta v\,(k',K')\right\}. \end{aligned} \tag{3.10}$$

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 $\{r,\ w,\ q_D,\ q_c\}$, 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.*

Our definition of equilibrium takes the labor requirement as given and determines an equilibrium direct subsidy such that both firms co-exist. In the simulations it is more convenient to take the direct subsidy as given and determine an equilibrium labor requirement. These definitions have identical allocations, so we do not distinguish between them.

The equilibrium first order condition and envelope equation determine aggregate capital accumulation:

$$u_c\left(C\left(K; s; l_G\right)\right) = \beta v_k\left(K', K'\right) \tag{3.11}$$

$$v_k\left(K, K\right) = u_c\left(C\left(K; s; l_G\right)\right)\left(\frac{\Omega}{Y\left(K; s; l_G\right)^{1-\phi}} r\left(K; s; l_G\right) + 1 - \delta\right) \tag{3.12}$$

$$C\left(K; s; l_G\right) = \Omega\frac{\psi}{\mu} Y\left(K; s; l_G\right)^{\phi} - K' + \left(1-\delta\right)K \tag{3.13}$$

$$Y\left(K; s; l_G\right) = A_P F\left(K - K_G\left(K; s; l_G\right), 1 - l_G\right) + A_G F\left(K_G\left(K; s; l_G\right), l_G\right) \tag{3.14}$$

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 and $w > srK_G\left(K\right) + S\left(K\right)$ for all K. Then a competitive equilibrium exists. Further, the equilibrium gross investment function $K' = H\left(K\right)$ is such that:*

1. $H_K\left(K\right) \geq 0$,
2. $C_K\left(K\right) \geq 0$,
3. $H\left(K\right)$ *satisfies the Euler equation derived from (3.11) and (3.12), and*
4. $H\left(K\right)$ *is concave.*

All proofs are in the Appendix. Theorem 1 requires total subsidies not exceed total wages, so that income remains positive, which is not very restrictive.[18]

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 in isolation. In particular, we consider a reduction in the interest

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[18] For Cobb-Douglas production with capital share α, $s < \left(1-\alpha\right)/\alpha$ is sufficient.

subsidy rate 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 relaxed 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:

$$\frac{\partial E}{\partial s} = \sigma_G \left(A_G F_k \left(K_G, l_G \right) \frac{\partial K_G}{\partial s} \right) - \sigma_P \left(A_P F_k \left(K - K_G, 1 - l_G \right) \frac{\partial K_G}{\partial s} \right). \tag{3.15}$$

Equation (2.9) implies the after-subsidy marginal products are equal. Hence:

$$= \left(\sigma_G \left(1 - s \right) - \sigma_P \right) r \left(K \right) \frac{\partial K_G}{\partial s}. \tag{3.16}$$

Equation (2.6) implies current period pollution is increasing in the subsidy if and only if:

$$\frac{\sigma_G}{\sigma_P} > \frac{1}{1-s}. \tag{3.17}$$

From equation (3.15), a decrease in the interest subsidy rate 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 $\frac{1}{1-s}$.

Let $\bar{x}$ denote the steady state value of any variable x. 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 $\left(\bar{\bar{K}}, \bar{\bar{E}} \right)$ with lower pollution ($\bar{\bar{E}} < \bar{E}$) and capital ($\bar{\bar{K}} < \bar{K}$).*

If condition (3.17) holds, then in addition:

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

3. *pollution falls:* $\frac{\partial E_t}{\partial s} > 0 \; \forall t \geq 0$.

If subsidized firms are sufficiently more pollution intensive, the capital reallocation resulting from a decrease in the interest subsidy rate causes current pollution to fall. This is the capital resource reallocation effect. 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. 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 (3.17) 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):

$$\frac{\partial E}{\partial s} = \frac{\partial \sigma}{\partial s} Y + \sigma \frac{\partial Y}{\partial s}. \tag{3.18}$$

After simplifying, we obtain:

$$\frac{\partial E}{\partial s} = (\sigma_G - \sigma_P) \frac{\partial K_G}{\partial s} \frac{r(K)\left((1-s)Y^P + Y^G\right)}{Y} - s\sigma \frac{\partial K_G}{\partial s} r(K). \tag{3.19}$$

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 (3.17), the technique effect dominates and a reduction in the subsidy rate causes pollution to fall. Reducing the interest subsidy rate 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 relaxing 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 conditions (3.17) and (2.8) hold. Then:*

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

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 (2.8) implies $\frac{1}{1-s}$ is larger than the wage ratio. Hence condition (3.17) is sufficient for the technique effect to outweigh the scale effect. Capital also moves to the private sector, so we have a capital reallocation effect, but condition (3.17) implies that the capital reallocation effect causes pollution to fall as well.

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 (2.8) holds. If condition (2.8) holds, as required by the theorem, then the interest rate falls and capital declines monotonically to a new steady state. Thus pollution declines monotonically to a new steady state below the initial drop in pollution.

If condition (2.8) does not hold, then steady state capital may rise or fall after the reduction in the labor requirement and the wage ratio is larger than $\frac{1}{1-s}$. Therefore current pollution will fall if σ_G/σ_P is greater than the wage ratio. If the steady state capital rises, steady state pollution rises unless σ_G/σ_P is large enough to offset the increase in steady state pollution caused by the increase in steady state capital.

For Cobb-Douglas production with labor share $1-\alpha$, both current and steady state pollution fall if:

$$\frac{\sigma_G}{\sigma_P} > \left(\frac{A_P (1-s)^{\alpha}}{A_G} \right)^{\frac{1}{1-\alpha}}. \tag{3.20}$$

In the calibration, condition (3.20) is satisfied for all pollutants.

Notice that if the conditions of Theorem 3 are 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 Theorem 3 gives sufficient conditions 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 (2.17) implies that this is equivalent to a shift of the world demand curve for the exported good, which increases Ω.

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 Ω 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 $\left(\bar{\bar{K}}, \bar{\bar{E}}\right)$ with higher pollution ($\bar{\bar{E}} > \bar{E}$) and capital ($\bar{\bar{K}} > \bar{K}$).*

Note that an increase in domestic tariffs increases Ω and pollution for $\psi(1-\zeta) < 1$ (satisfied if $\zeta = 0$). If both foreign and domestic tariffs fall in a trade treaty, then the effect on Ω 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 the conditions of Theorem 3 hold. The reason is that first both foreign and domestic tariffs generally fall, so the effect on Ω is ambiguous. But even if Ω 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 (AGE) 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.[19] The computational model is an extension of Bajona and Chu (2008) that allows for international trade (capital markets are still closed).

We start with the theoretical model of Section 2, with functional forms:

$$u(c) = \frac{c^{\rho} - 1}{\rho}, \quad F(K, l) = K^{\alpha} l^{1-\alpha}. \tag{4.1}$$

Next, we add several features which result in a more realistic calibration and better quantitative predictions. First, we assume the population N grows at exogenous rate n, and that A_G and A_P grow at exogenous rate $(1+\gamma)^{1-\alpha} - 1$. The Armington aggregator in the production of the aggregate good is CES:

$$Y_C = Z \cdot \left(\mu X_D^{\zeta} + (1-\mu) M^{\zeta}\right)^{\frac{1}{\zeta}}. \tag{4.2}$$

Here $\frac{1}{1-\zeta}$ is the elasticity of substitution between the domestic and foreign produced goods and Z is a technology parameter.

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 for quantitative predictions. Therefore, following Lucas and Prescott (1971), we model sectoral and temporal adjustment costs as:

$$I = nK_i' - \mathrm{AC}\left(\frac{I_i}{K_i}\right) K_i - (1-\delta) K_i. \tag{4.3}$$

Here I is net investment and AC is the adjustment function which satisfies:

$$\mathrm{AC}\left(\frac{I}{K}\right) \equiv \left((n\gamma - 1 + \delta)^{1-\theta} \left(\frac{I}{K}\right)^{\theta} - (1-\theta)(n\gamma - 1 + \delta)\right) \frac{1}{\theta}, \quad 0 < \theta \leq 1. \tag{4.4}$$

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[19] None of these features are critical for our qualitative analysis of the effect of subsidies on pollution and, therefore, the intuition from the simplified model applies to the quantitative model.

The computational model also adds exogenous government purchases per capita, G, and taxes on producers of final goods, T, which better matches China's revenue sources. The government budget constraint is now:

$$q_c G + s\hat{r}K_G + S + \hat{TR} = TF + T. \tag{4.5}$$

Here production tax revenues are:

$$T = q_D tY. \tag{4.6}$$

The government budget constraint remains 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 (2.16), where $\hat{D}$ now grows exogenously at rate γ, 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 2.18 holds), and domestic and foreign demand for the traded good must equal supply (equation 2.21 holds). The domestic market for the aggregate good also clears:

$$C + I + G = Y_c. \tag{4.7}$$

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

$$E = \frac{\sigma_G Y_G + \sigma_P Y_P}{EI}. \tag{4.8}$$

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

4.2 Data and Calibration

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. In 1997, SOE share of industry value added was less than 12% for all industry classifications (and less than 8% in 2006), which lends support to the competitive model. 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 then subsidize capital rental by SOEs. SOEs are heavily subsidized and the bulk of subsidies to be reduced in the WTO Agreement are subsidies to SOEs. Thus, our calibration strategy will be to assume that SOEs receive subsidies, while private enterprises do not.

We calibrate the of the model following the same technique as Bajona and Chu (2008), 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 calibration of the trade-related parameters follows standard procedures in AGE models. The values of the calibrated parameters are reported in Table 1.

For the critical emissions intensity parameters, national and industry level emissions data is available for four pollutants, but SOE emissions are not reported separately.[20] However, industry emissions and SOE industry shares are available, and so we estimate the aggregate SOE pollution intensity using industry data.

4.2.1 Data

We gathered industry emissions data for air pollutants SO_2, soot, and industrial dust and for the water pollutant COD from various editions of the *China Environment Yearbook* (1996-2007 covering years 1995-2006). Industry air pollutant emissions data is also available from various editions of the *Chinese Statistical Yearbook* (1996-2006 covering years 1995-2005). In general the data are identical, but a few (less than five) data points show obvious recording errors in one source or the other, which were corrected. Reported emissions are the total of a survey of firms which account for 85% of emissions, and an estimate of the remaining 15% of emissions.

China switched their industry classification system twice during the period of data coverage. The three classification systems are 1984, 1994, and 2002, designated for the year in which industry output data began reporting under the given classification. However, emissions data was reported using the 1984 classification system until 2001, and then was reported using the 1994 classification system for 2001 and 2002 before switching to the 2002 classification system in 2003. Finally, emissions data includes a few industry categories not available in the output data (such as cement). These industries cannot be used since SOE share data does not include these categories.

The *China Statistical Yearbook* (1996-2007, hereafter CSY) reports nominal value added by industry for 1995-2006 for both industrial SOEs and all industrial firms, with the exception of 1998 and 2004. From the nominal value added data, we construct industry SOE shares and

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[20] Wang and Jin (2007) gathered firm level data for total suspended solids. They find that SOEs are about 57% more pollution intensive than non-SOEs, even after controlling for some industry effects, which is broadly consistent with our results below.

industry shares of total value added. In 1998, however, China changed both the definition of an SOE and the scope of coverage of the value added measure. Specifically, firms in which the state held a controlling share were reclassified from private to state-owned. Firms with size smaller than five million yuan were no longer included in the value added measure after 1998. Since state-owned firms tend to be large, both changes dramatically increased the measured SOE shares in 1999. Despite an overall downward trend in SOE shares (for example, from 1996-7 SOE shares increased in only three industries), SOE shares increased in 17 of 18 industries from 1997-9, presumably due to the measurement changes.

For the price deflators, Holz (2006) reports real and nominal gross output value (GOV) data (1990 prices) by industry for 1993-2002 using the the 1994 classification system, which is in turn collected from various statistical yearbooks. GOV is a measure of revenue, not value added. Firms directly report real GOV data. However, some question the accuracy of the implicit price deflators derived from reported data (see for example Young 2003). The *CSY* (2006-7) reports ex-factory (producer) price indices of industrial products derived independently from the reporting firms for the years 2002-2006 (2001 is the base year). We use the Holz data until 2001 and the ex-factory price indices for 2002-2006, which results in the largest data set. The results were little changed regardless of the deflator used in 2001 and 2002, the years for which both deflators exist. We removed any new industry categories introduced in 2003 since no data is available to convert to 1990 prices. Further, the Holz data must be aggregated to be applied to the 1995-2000 emissions data, since Holz's data uses the 1994 classification system.

Later industry classifications are more detailed, although some are unchanged across the entire data set. The 1984 system has 18 usable industries, the 1994 system has 23 industries which are new or for which the classification system changed, with 3 old classifications no longer being reported. The 2002 classification adds many new industries which cannot be used since we cannot convert the price data to 1990 dollars. Hence we have a panel of 41 industries, some of which begin or end in 2001.[21] Three industries which begin in 2001 end in 2002 (two are discontinued and one is missing deflator data).

The usual caveats about working with Chinese data, especially price data, certainly apply here. The results are robust to alternative data sources, which adds confidence to our results. In section 6, we perform sensitivity analysis to account for uncertainty in the estimated emissions intensity parameters. In total, we have 263 observations, an unbalanced panel of 41 industry classifications over 10 years.

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[21] Controlling for industry fixed effects using more aggregate industry classifications in general produced poor results, since aggregate classifications include both low and high emission industries.

4.2.2 Industry level calibration: estimation strategy

Let i denote industries, then applying equation (2.26) by industry gives:

$$\frac{E_{it}}{Y_{it}} \equiv \frac{E_{Pit}}{Y_{it}} + \frac{E_{Git}}{Y_{it}}. \tag{4.9}$$

Let $v_{it} \equiv \frac{Y_{Git}}{Y_{it}}$ denote the SOE share in industry i, then:

$$\sigma_{it} \equiv \sigma_{Pit}\left(1 - v_{it}\right) + \sigma_{Git} v_{it}, \tag{4.10}$$

$$\equiv \sigma_{Pit} + \left(\sigma_{Git} - \sigma_{Pit}\right) v_{it}. \tag{4.11}$$

Equation (4.11) implies pollution intensity is a linear function of the SOE share. Both the intercept and slope terms are time and industry specific. To estimate such a model requires industry dummies, terms in which industry dummies are interacted with total industry SOE share, plus parameters accounting for time related changes in emissions intensity. Unfortunately, it is infeasible to estimate this equation, since we have only 263 data points. Therefore, we assume the slope is constant within industry groups. It turns out the choice of groups has little effect on the results, and the slope is fairly constant across industries. However, we expect the slope term to be smaller after 1998. Enterprises in which the state owns a simple majority interest are unlikely to have the same bargaining power over environmental compliance as enterprises wholly owned by the state. Imposing these restrictions implies:

$$\left(\sigma_{Git} - \sigma_{Pit}\right) = \eta_1 + \eta_2 \cdot 1(t > 1998) + \xi_{1it},\ \xi_{1it} \sim \text{ iid mean } 0. \tag{4.12}$$

Here $\eta_1 = \left(\sigma_G - \sigma_P\right)_{t<1998}$ is the parameter of interest, while $\eta_1 + \eta_2$ measures slope the after 1998. We focus on η_1 since most subsidy reductions in the WTO agreement are for SOEs wholly owned by the state. For the constant term, we employ a fixed effects specification:

$$\sigma_{Pit} = \sigma_{Pi} + Q\left(\eta, t\right) + \xi_{2it},\ \xi_{2it} \sim \text{ iid mean } 0. \tag{4.13}$$

Here Q is a function which measures reductions in emissions intensity over time, due to technical change and possibly changes in data measurement. With these assumptions we can then estimate the η parameters using:

$$\sigma_{it} = \eta_{0i} + \eta_1 v_{it} + \eta_2 v_{it} 1\left(t > 1998\right) + Q\left(\eta, t\right) + \xi_{it}, \tag{4.14}$$

$$\xi_{it} = \xi_{1it} v_{it} + \xi_{2it}. \tag{4.15}$$

According to specification (4.14), the errors will be heteroskedastic. We will consider for Q a simple time trend and year dummies.

Given estimated coefficients $\hat{\eta}_{0i}$ and $\hat{\eta}_1$, it is straightforward to sum across industries to obtain an estimate of the aggregate pollution intensity. Let $size_{it} \equiv \frac{Y_{it}}{Y_t}$ be the industry share of value added and normalize Q so that $Q(\eta, 1997) = 0$, then:

$$\hat{\sigma}_{1997} = \sum_{i=1}^{n-1} \hat{\eta}_{0i} \cdot \text{size}_{i,1997} + \hat{\eta}_1 v_{1997}. \tag{4.16}$$

Aggregate emissions intensities are then:

$$\sigma_P = \sum_{i=1}^{n-1} \hat{\eta}_{0i} \cdot \text{size}_{i,1997} \quad , \tag{4.17}$$

$$\sigma_G = \sigma_P + \hat{\eta}_1. \tag{4.18}$$

One possible problem with using the industry specific effects coefficients to find σ_P is that the industry specific coefficients may be estimated imprecisely, especially for industries with few data points. An alternative is to combine equations (2.26) and (4.18) so that:

$$\sigma_P = \sigma - \hat{\eta}_1 v_G. \tag{4.19}$$

Hence given we can find the aggregate private sector pollution intensity as the economy wide average pollution intensity in the data less the estimated contribution of the SOE sector pollution intensity to the economy wide average.

Our fixed effects estimation strategy accounts for industry specific variation in pollution intensity. We are thus using within-industry variation over time (apart from the aggregate time trend) to estimate the difference in emissions intensity between SOEs and private firms. Therefore, a reduction in subsidies to a particular industry (e.g. coal) generates reductions in emissions intensity in the coal industry as private firms with cleaner technologies replace SOEs (the technique effect).

4.2.3 Estimation Results

In addition to estimating (4.14) using fixed effects, a number of variations were tried to check for robustness. The results are not sensitive to the mixture of price deflators used, the inclusion of an industry share variable, various other specifications such as log and cubic, and the significance of the key coefficient η_1 is not sensitive to using alternative output measures. The results are sensitive to which time variables are included. Thus we report the results for fixed effects, with and without time variables.

Tables 2-3 report the estimation results for OLS, fixed effects, fixed effects including a time trend (our preferred model), and fixed effects with year dummies. All t-statistics are calculated using standard errors corrected for heteroskedasticity using the White procedure.[22]

Comparing columns (1) and (2), we see the importance of industry fixed effects. Most of the variation in pollution intensity across industries is due to industry variation unrelated to the SOE share. The key coefficient $\hat{\eta}_1$, which measures differences in emissions intensity between SOEs and private firms is positive and significant for all pollutants, for the fixed effects specification (column 2). Hence, even after controlling for industry specific fixed effects, SOEs are more pollution intensive. However, for all pollutants the magnitude of $\hat{\eta}_1$ is unrealistically large. For example, the SOE sector accounts for about 46% of value added and economy wide average emissions intensity for COD is 0.57 tons per hundred thousand 1990 yuan. Thus, to reconcile a very large difference in pollution intensity between private firms and SOEs requires σ_P to be negative for COD.

One possibility is that aggregate pollution is falling over time for reasons unrelated to falling SOE shares, thus magnifying the estimate $\hat{\eta}_1$. When a time trend (column 3) or time dummies (column 4) are added, η_1 remains positive but loses significance for soot and COD.[23] The magnitude of $\hat{\eta}_1$ falls for all pollutants. The addition of time variables does little to improve the fit of the model (none of the time dummies are significant for any pollutant), but η_1 is in its theoretical range. Apparently, for soot and COD, the data does not have enough within-industry, within-year variation to pin down η_1 very precisely. Therefore, for calibration purposes, we use regression (3) to calibrate $\hat{\eta}_1$. We conduct a sensitivity analysis and vary η_1 to account for the uncertainty of the estimate.

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 sometimes not clear which subsidies are reduced for what reason, we focus instead

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[22] Stock and Watson (2008) show that White's procedure is inconsistent holding time fixed as the number of industries increases, but their correction requires all industries to have observations in at least three time periods. Discarding the data with two time periods and using their correction did not materially alter the results.

[23] Other empirical specifications of the time trend were also tried with similar results.

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 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 prior to the reform period 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. Tariffs and interest subsidy rates remain at their 1997 values. Direct subsidies were already in a downward trend before the WTO agreement, as China was in a process of industrial reform. In the benchmark economy we assume that direct subsidy rates continue in the same downward trend during the reform period as in the pre-reform period and stabilize afterward. In the other four experiments, policies change over the 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, direct subsidies in the reform period are reduced an additional 25.98%, compared to benchmark (in line with WTO requirements). 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. The reduction in direct subsidies is achieved by reducing the labor requirement by 6.5% over the reform period. The labor requirement reduction moves labor to the private sector. The movement of labor to the private sector increases the marginal product of capital in the private sector, so capital also moves to the private sector. Both of these effects slightly raise the long run output level by 0.1%, 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 4 and Figures 1-4, long run pollution falls relative to the benchmark for all four pollutants, from a decrease of 2.7% in soot to a 6.3% decrease in dust. These results are consistent with the prediction of Theorem 3, since $\sigma_G/\sigma_P > 1/(1-s) = 2.3$ for all four pollutants. Thus the second experiment has lower pollution than the benchmark, because SOEs are sufficiently more pollution intensive so that the technique effect is large enough to overcome the scale effect.

The third experiment shows the effect of a 2% reduction in the interest subsidy rate, holding the reduction in direct subsidies during the reform period at benchmark levels. This is achieved with a reduction in the labor requirement of 10.2% over the reform period. 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 calibration sets the interest subsidy rate to match the difference in the capital to labor ratio between private firms and SOEs. Table 1 indicates that SOEs use 60% of the capital, but employ only 40% of the labor. To explain the high capital to labor ratio of SOEs, the model requires an interest subsidy rate of 0.57.[24]

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 4 and Figures 1-4, steady state emissions of all four pollutants fall relative to the benchmark, from a 4.9% fall in soot to a 10.9% fall in dust.

The fourth experiment combines the two changes in policies. It shows the effect of a 2% reduction in the interest subsidy rate, together with an additional 25.98% decrease in direct subsidies in the reform period. This is achieved with a 18.4% reduction in the labor requirement. The fall in pollution is larger; the long run output level decreases by only 0.1% relative to benchmark, since the lower investment is not completely offset by labor moving to the higher TFP private sector. The reductions in pollution range from 8.1% for dust to

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[24] Our subsidy rate is lower than the value used by Fisher-Vanden and Ho (2007) of 0.9 in 1995. In turn, this estimate is based on data provided by Lardy (1998), who finds the reported nominal interest rate for working capital was 10.98% and calculates a nominal market rate equal to the 17.1% CPI inflation rate plus a 4% real return. This methodology is sensitive to the inflation rate and the assumption that the reported nominal rate is the capital weighted average rate among SOEs and private firms. Using their methodology yields negative subsidies for 1997, since inflation was only 2.8% while the nominal rate was 8.64%.

18.7% for soot.

The final experiment supposes the rest of 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 4 and Figures 1-4, pollution rises, since in this case no technique effect exists. Pollution increases by 0.5% for all pollutants relative to the benchmark. Notice that since there is no technique effect, the reduction in world tariffs has the same effect in both sectors and, thus, the effect is the same for all pollutants. 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 57% discount on their capital rental, so a 2% reduction in the interest subsidy rate has quantitatively large effects (it accounts for total interest subsidies being 20.3% lower as percentage of GDP than in the benchmark economy at the end of the reform period). 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 in foreign demand.

Figure 5 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 industrial dust. 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 Sensitivity Analysis

The estimation procedure used in Section 4.2 does not determine the parameter η_1 very precisely for soot and COD. In this section we perform sensitivity analysis on the value of η_1. We run again the simulations in Section 5 changing η_1 in two different ways. First, we reduce η_1 by one standard deviation.[25] Second, we use the values of η_1 estimated in the regression model with dummies (model 4 in Tables 2-3).[26] We obtain that, in both cases, the qualitative results of Section 5 remain unchanged. In particular, long run pollution intensity

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[25] For COD, reducing η_1 by one standard deviation implies a negative σ_G. We reduce η_1 by half a standard deviation instead.

[26] For COD the regression implies a negative number for σ_G. In this case, we use the estimated η_1 from simulation (3) together with the implied σ_P from simulation (4) to infer a new σ_G.

decreases for all pollutants in all experiments that involve a reduction in SOE subsidies.[27] The magnitude of the changes are, though different.

Table 5 presents long run pollution intensities relative to benchmark for two sensitivity analysis exercises. It shows that reducing η_1 by one standard deviation decreases the long run improvements in pollution intensity by 50% for soot and COD, 20% for SO_2, and 7% for dust. These differences are stable across all experiments that involve subsidy reductions. When the estimates of η_1 from the regression with time dummies are used, we obtain very similar results. The differences are now reduced by 50% for soot, 35% for COD, 25% for SO_2, and a negligible amount for dust. Therefore, this sensitivity analysis shows that, as expected, the magnitudes of the changes in pollution intensity depend on the particular estimate of η_1, but the general pattern and the sign of the improvements are robust to changes in η_1.

7 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 our numerical section shows that the reduction in direct subsidies to Chinese SOEs required by WTO accession reduces pollution for all 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. For example, granting monopoly powers may cause SOEs to reduce output and therefore pollution. If so, reducing subsidies may cause a larger scale effect than our model indicates. Nonetheless, SOE shares of value added

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[27] In the experiment where only tariffs are reduced, the results remain unchanged. This is not surprising, given that in this experiment there is no technique effect and, thus, changes in relative pollution have no effect in the economy.

are small for most industry classifications in China, which supports the competitive model at least for China. Finally, our model has only one 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).[28]

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 subsides are both richer and have 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.

8 Appendix: Proof of theorems

8.1 Proof of Theorem 1

Substituting the interest rate (2.2), wage rate (2.3), and transfer (2.20) into the budget constraint for the aggregate good (3.7) and simplifying results in:

$$c + k' = \mathcal{G}(k, K; s), \tag{8.1}$$

$$\begin{aligned}\mathcal{G}(k, K; s) \equiv \; & \Omega \frac{\psi}{\mu} Y(K; s)^{\phi} + \frac{\Omega A_P F_k (K - K_G(K; s), 1 - l_G)}{Y(K; s)^{1-\phi}} (k - K) + \\ & (1 - \delta) k, \end{aligned} \tag{8.2}$$

$$Y(K; s) \equiv A_P F(K - K_G(K; s), 1 - l_G) + A_G F(K_G(K; s), l_G). \tag{8.3}$$

The model is now in the framework of Greenwood and Huffman (1995) (GH). Using the condition given in the theorem and repeatedly appealing to (2.9), and the properties of the

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[28] 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.

interest rate and the share of capital in the subsidized sector (conditions 2.6 and 2.7), we can verify assumptions (i)-(iii) of GH. It follow from their proposition on page 615 that an equilibrium exists.

Further, equation (3) of GH states that the equilibrium investment function H is the fixed point 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 GH states that H has the following properties:

$$0 \leq H_K(K) \leq \mathcal{G}_1(K, K) + \mathcal{G}_2(K, K), \tag{8.4}$$

$$0 < H(K) < \mathcal{G}(K, K). \tag{8.5}$$

Equation (8.4) implies that $c(K)$ is increasing in K. Thus since u is concave, for all K, K':

$$(u_c(c(K)) - u_c(c(K')))(K - K') \leq 0. \tag{8.6}$$

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.

8.2 Proof of Theorem 2

As shown in the text, condition (3.17) implies a decrease in the subsidy decreases pollution.

For the steady state, let $\beta = \frac{1}{1+\lambda}$, where λ is the rate of time preference. Evaluating equations (3.11) and (3.12) at the steady state $\bar{K}$ yields the modified golden rule:

$$\lambda = \Omega Y\left(\bar{K}; s\right)^{\phi-1} r\left(\bar{K}; s\right) - \delta \tag{8.7}$$

Now since steady state income, $Y\left(\bar{K}; s\right)$ is decreasing in the subsidy, $\phi < 1$, and $r\left(\bar{K}; s\right)$ is increasing in the subsidy, the right hand side is increasing in the subsidy. Further, since $Y\left(\bar{K}; s\right)$ is increasing in $\bar{K}$, $\phi < 1$, and $r\left(\bar{K}; s\right)$ 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 $\bar{E}$ is increasing in s given $\sigma_G > \sigma_P$, using (8.7).

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 $\bar{\bar{K}}$ from above, since $K_0 > \bar{\bar{K}}$. Given that pollution is increasing in the capital stock, pollution will also converge monotonically from above to $\bar{\bar{E}}$.

8.3 Proof of Theorem 3

First, given $A_p(1-s) < A_G$, equation (2.5) implies:

$$F_K(K_P, l_P) > F_K(K_G, l_G). \tag{8.8}$$

Because F is concave and constant returns to scale, equation (8.8) implies the government sector is more capital intensive ($\frac{K_P}{l_P} < \frac{K_G}{l_G}$). Thus, since F_K/F_l is a decreasing function of the capital to labor ratio:

$$\frac{1}{1-s} > \frac{w}{w_G}, \tag{8.9}$$

and thus the ratio of emissions intensities is larger than the wage ratio.

Differentiating pollution with respect to l_G, holding K fixed, we see that current pollution falls given conditions (3.17) and (8.9). In addition, differentiating the steady state pollution with respect to l_G implies that steady state pollution falls given conditions (3.17) and (8.9). Let $E_0 < \bar{E}$ denote the new pollution emissions in the initial period.

For periods between 0 and the steady state, steady state capital also falls given $A_p(1-s) < A_G$, so pollution will decline to the new steady state $\bar{\bar{E}} < E_0$. The reasoning is identical to Theorem 2.

8.4 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 Ω. For the steady state, note that modified golden rule (8.7) for this economy implies that if Ω 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.

9 Appendix: Tables and Figures

Parameter	Symbol	Value	Source
Production Parameters			
Capital Share	α	0.36	(a)
Productivity, Private Sector	A_P	1.48	(a)
Productivity, SOEs	A_G	1.05	(a)
Growth rate, productivity	γ	1.02	US trend
Armington Aggregator			
Technology Parameter	Z	1.87	Equilibrium
Elasticity Parameter	ζ	0.50	AGE literature
Share Parameter	μ	0.63	I/O, Equilibrium
Investment Parameters			
Depreciation	δ	0.08	Investment Data
Adjustment Costs Parameter	θ	0.90	US I/K volatility
Preference Parameters			
Discount Rate	β	0.96	one-year period
Elasticity Parameter	ρ	0.00	within RBC range
Foreign Demand	$\hat{D}$	0.62	I/O
Population Growth	n	0.01	Demographic data
Policy Parameters			
Production Tax	t	0.30	(a)
Government Consumption	G	0.30	I/O
Rental rate subsidy	s	0.57	(a)
Initial SOE labor share	l_G/l	0.40	(a)
Initial Values			
Initial Private Capital	K_{P0}	1.87	K series
Initial Government Capital	K_{G0}	2.81	K series

Table 1: Economic parameter values. (a): Jointly calibrated to match the SOE shares of capital and labor for 1997, the SOE losses as a percentage of GDP in 1997, capital and labor income from the I/O (input-output) table, and domestic output for 1997.

For Tables 2-3, models are (1) OLS, (2) fixed effects, (3) fixed effects with time trend, and (4) fixed effects with time dummies. T-statistics calculated using standard errors corrected for heteroskedasticity are below the coefficients, and an asterisk indicates significance at the 95% level. Units for pollution intensity are tons per hundred thousand 1990 yuan.

	SO_2				Soot			
Econometric Model	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
constant	-0.36* (-2.16)				-0.13 (-1.60)			
$\sigma_G - \sigma_P = \eta_1$	2.77* (2.67)	2.20* (7.96)	1.22* (2.78)	0.95* (2.05)	1.40* (2.35)	1.26* (5.63)	0.54 (1.65)	0.28 (0.81)
η_2	-1.60 (-1.57)	-1.23* (-4.23)	-0.95 (-3.01)	-1.45* (-3.01)	-0.93 (-1.64)	-0.65* (-2.83)	-0.45 (-1.84)	-0.90* (-2.39)
$\eta_1 + \eta_2$	1.17 (0.24)	0.96* (2.96)	0.27 (0.70)	-0.50 (-0.86)	-1.06 (0.21)	0.60* (2.17)	0.09 (0.29)	-0.62 (-1.32)
Implied σ_G	2.50	2.19	1.67	1.53	1.30	1.22	0.84	0.70
Implied σ_P	-0.28	-0.01	0.45	0.58	-0.10	-0.04	0.30	0.42
Industry share	11.63* (2.46)	-26.26* (-2.28)	-28.1* (-2.49)	-26.33* (-2.36)	5.98* (2.70)	-15.76 (-1.73)	-17.11 (-1.91)	-15.58 (-1.78)
Time trend			-0.03* (-2.87)				-0.02* (-2.82)	
1995 Time Dummy				0.13 (0.75)				0.16 (1.18)
1996 Time Dummy				-0.03 (-0.17)				0.01 (0.10)
1999 Time Dummy				0.28 (1.29)				0.33 (1.57)
2000 Time Dummy				0.23 (1.24)				0.22 (1.36)
2001 Time Dummy				0.15 (0.88)				0.19 (1.36)
2002 Time Dummy				0.07 (0.46)				0.13 (1.03)
2003 Time Dummy				-0.04 (-0.26)				0.05 (0.40)
2005 Time Dummy				-0.14 (-1.03)				-0.04 (-0.40)
2006 Time Dummy				-0.19 (-1.39)				-0.09 (-0.85)
R^2	0.216	0.953	0.954	0.956	0.196	0.881	0.882	0.887
Adjusted R^2	0.207	0.944	0.945	0.945	0.187	0.857	0.859	0.859

Table 2: Regression coefficients and results for SO_2 and soot, 263 observations.

	Industrial Dust				COD			
Econometric Model	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
constant	0.25* (3.07)				0.62* (3.17)			
$\sigma_G - \sigma_P = \eta_1$	0.03 (0.08)	2.15* (3.19)	1.87* (2.80)	1.86* (2.72)	1.15 (1.67)	3.70* (2.53)	0.92 (0.69)	1.40 (1.09)
η_2	-0.27 (-0.94)	-0.26 (-1.74)	-0.18 (-1.18)	-0.70* (-2.20)	-1.41 (-1.93)	-1.08* (-2.56)	-0.28 (-0.74)	0.78 (1.13)
$\eta_1 + \eta_2$	-0.24 (-0.10)	1.89* (2.61)	1.68* (2.35)	1.16* (2.12)	-0.26 (-0.06)	2.62* (2.27)	0.64 (0.60)	2.18 (1.44)
Implied σ_G	0.99	2.12	1.97	1.96	1.18	2.53	1.04	1.31
Implied σ_P	0.96	-0.03	0.10	0.10	0.03	-1.16	0.14	-0.09
Industry share	4.14 (1.80)	8.34 (0.84)	7.80 (0.83)	9.98 (1.07)	-6.10 (-1.76)	-0.59 (-0.09)	-5.83 (-0.85)	-9.59 (-1.08)
Time trend			-0.01 (-0.67)				-0.09* (-2.56)	
1995 Time Dummy				-0.23 (-1.71)				0.12 (0.19)
1996 Time Dummy				-0.27 (-1.79)				-0.19 (-0.41)
1999 Time Dummy				0.35 (0.74)				-0.86 (-1.22)
2000 Time Dummy				0.17 (0.61)				-0.93 (-1.38)
2001 Time Dummy				-0.13 (-0.78)				-1.24 (-1.82)
2002 Time Dummy				-0.13 (-0.76)				-1.24 (-1.84)
2003 Time Dummy				-0.17 (-0.89)				-1.22 (-1.82)
2005 Time Dummy				-0.13 (-0.65)				-1.12 (-1.82)
2006 Time Dummy				-0.15 (-0.70)				-1.11 (-1.70)
R^2	0.013	0.780	0.780	0.790	0.029	0.666	0.672	0.681
Adjusted R^2	0.002	0.737	0.736	0.738	0.018	0.600	0.605	0.603

Table 3: Regression coefficients and results for industrial dust and COD, 263 observations.

	Steady State as a Percent of Baseline				
Experiment	Y	soot	COD	SO_2	dust
Decrease S by 26%	0.10	-2.69	-4.99	-3.44	-6.35
Decrease s by 2%	-0.27	-4.87	-8.67	-6.10	-10.91
Decrease s 2%, S 26%	-0.10	-8.14	-14.77	-10.29	-18.68
Decrease τ_F to 0	0.48	0.48	0.48	0.48	0.48

Table 4: Results of numerical experiments.

	Steady State as a Percent of Baseline				
η_1 Reduced by One Standard Deviation					
Experiment	Y	soot	COD	SO_2	dust
Decrease S by 26%	0.10	-1.32	-2.56	-2.63	-5.88
Decrease s by 2%	-0.27	-2.61	-4.65	-4.77	-10.14
Decrease s 2%, S 26%	-0.10	-4.19	-7.75	-7.96	-17.34
Decrease τ_F to 0	0.48	0.48	0.48	0.48	0.48
η_1 From Regression with Time Dummies					
Experiment	Y	soot	COD	SO_2	dust
Decrease S by 26%	0.10	-1.25	-3.18	-2.53	-6.34
Decrease s by 2%	-0.27	-2.50	-5.68	-4.60	-10.90
Decrease s 2%, S 26%	-0.10	-3.99	-9.54	-7.67	-18.66
Decrease τ_F to 0	0.48	0.48	0.48	0.48	0.48

Table 5: Sensitivity analysis: Results of numerical experiments.

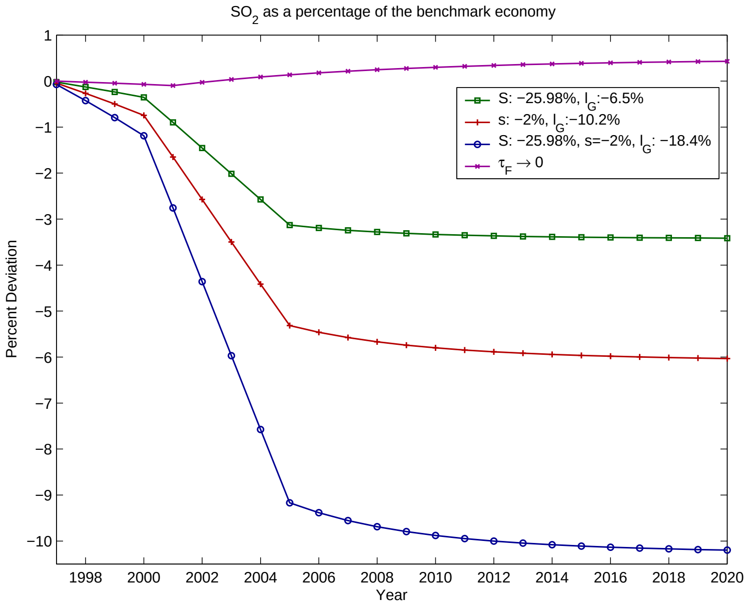

Figure 1: Sulfur Dioxide Emissions relative to emissions in the benchmark economy. Changes in tariffs and subsidies are phased in over years 2000-2004.

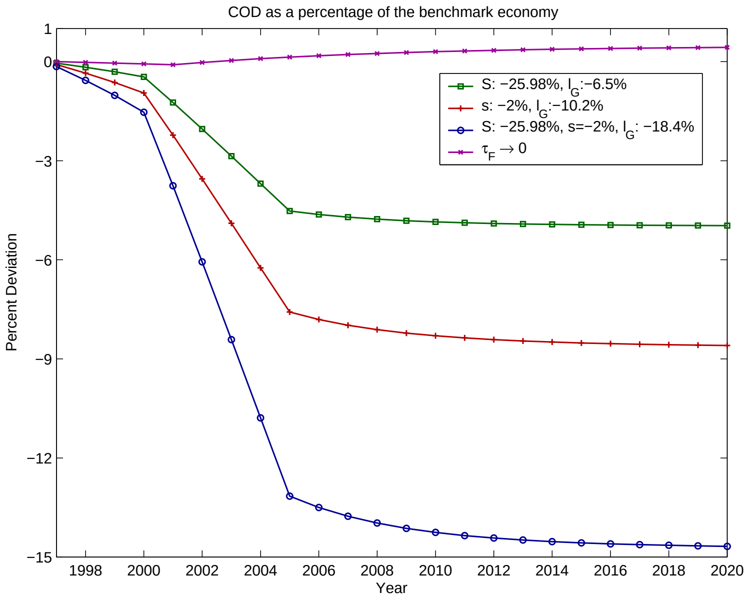

Figure 2: Chemical oxygen demand relative to demand in the benchmark economy. Changes in tariffs and subsidies are phased in over years 2000-2004.

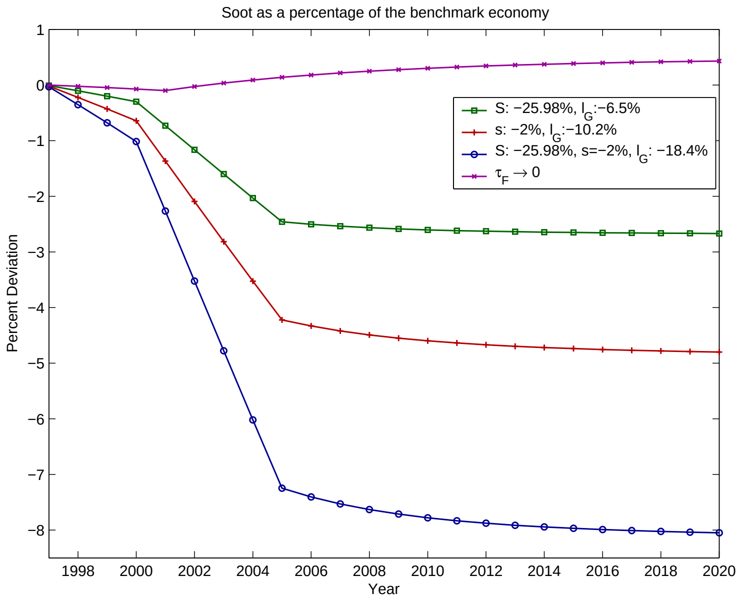

Figure 3: Soot Emissions relative to emissions in the benchmark economy. Changes in tariffs and subsidies are phased in over years 2000-2004.

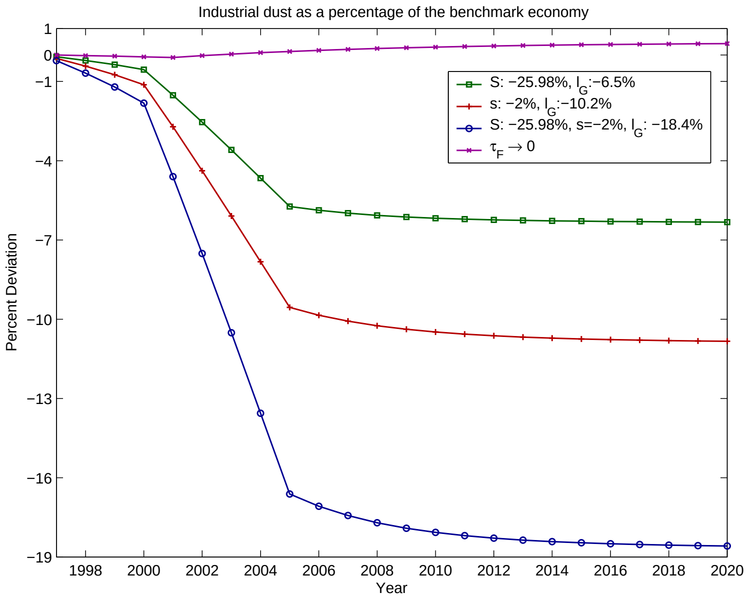

Figure 4: Industrial dust emissions relative to emissions in the benchmark economy. Changes in tariffs and subsidies are phased in over years 2000-2004.

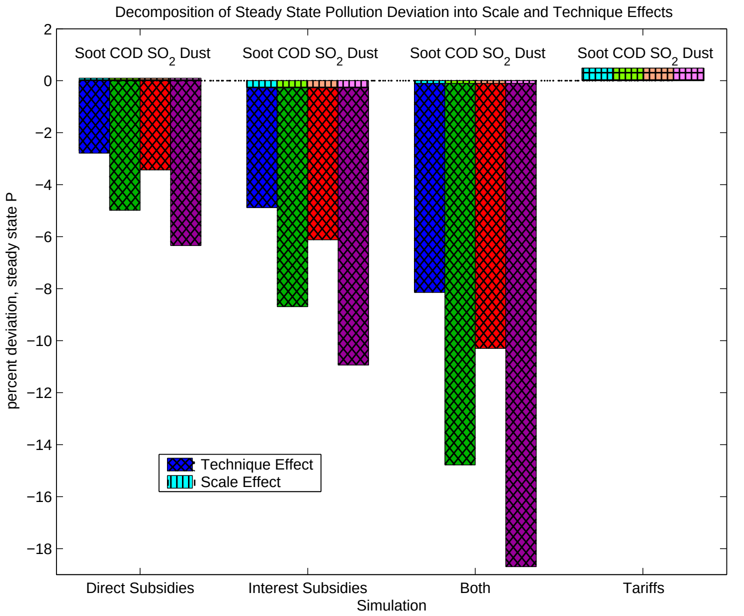

Figure 5: Decomposition of steady state change in pollution relative to the benchmark economy into scale and technique effects.

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