

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

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February 6, 2012

*We would like to thank Libby Ashley, Emily Blanchard, Karen Fisher-Vanden, Amy Glass, Linda Goldberg, Charles Mason, Carol McAusland, Oscar Mitnik, Maurice Roche, M. Scott Taylor, two anonymous referees, and seminar participants at the University of Calgary, the University of Miami, the University of Western Ontario, the National Bureau of Economic Research Summer Institute, and the Eighth Occasional California Workshop on Environmental and Natural Resource Economics for comments and suggestions.

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, and find that pollution has a more elastic response to reducing subsidies than to reducing tariffs. While a 5% reduction in tariffs increases all pollutants by approximately 1%, a 5% reduction in subsidies reduces pollution by 1.8-11.6%, depending on the pollutant. The reductions in pollution occur without any environmental side agreements or abatement policy changes.

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 of 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 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 calibration, the condition is satisfied for all three 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 pollution has a more elastic response to reducing subsidies than to reducing tariffs. While a 5% reduction in tariffs increases all pollutants by approximately 1%, a 5% reduction in subsidies reduces pollution by 1.8-11.6%, depending on the pollutant.

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

The reductions in pollution occur without any environmental 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. 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 lack 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 SO₂ 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

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

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 SO₂ 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 SO₂.

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 subsidies. The subsidies are typically in industries facing foreign competition. The reduction in subsidies affects the share of production by subsidized firms, total production, terms of trade, and capital accumulation, each of which has an effect on pollution.

The related literature on how perverse subsidies to industry affect the environment is less developed.³ 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 (2010) 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 non-subsidized (hereafter 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.⁴ In exchange, subsidized firms receive direct (cash) subsidies to cover the negative profits that result from the use of an inefficient mix of capital and labor.⁵ Subsidized firms also receive low interest loans from the government or state owned banks, modeled as an interest rate subsidy.⁶ Finally, subsidized

³Barde 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 Zaniias 1998).

⁴Although the labor requirement is exogenous, it is consistent with the idea that subsidized firms increase employment to increase bargaining power with the government (Yin 2001).

⁵Direct subsidies can thus be thought of as “bailouts” for firms in danger of exiting the market due to negative profits.

⁶We are ignoring many other types of subsidies, see Barde and Honkatukia (2004) for a partial list. In a subsequent paper, Kelly (2009) ranks many types of subsidies according to their environmental damage in a theoretical, closed economy setting. In contrast, here we determine the effect on pollution of reducing

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.

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 result 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.

the two subsidies that are the main focus of trade agreements such as the US-China bilateral agreement, in an environment with trade. Further, in our setting, subsidies generate terms of trade effects which are not present in Kelly (2009).

We calibrate the model to China in 1997, and simulate the effect on pollution emissions of reducing direct subsidies, interest subsidies, and tariffs. An important set of parameters are the relative emissions intensities between subsidized SOEs and private firms, which we assume are not subsidized. We estimate the emissions intensities using a panel of Chinese industry level data from 1995-2007, and find SOEs have significantly higher emissions intensity than private firms for three of four pollutants tested, controlling for industry and time specific effects.

We simulate the effect of reducing direct subsidies targeted for elimination by the US-China bilateral WTO trade agreement, and find a surprisingly strong technique effect. Antweiler, Copeland, and Taylor (2001) also find a strong technique effect using different data, which they attribute to an income effect on abatement policy. Our technique effect comes from a different source: reductions in subsidies required by a trade agreement concentrate production in more productive but less pollution intensive firms. This reduces pollution emissions intensity, while increasing income. Our technique effect is therefore an alternative explanation for the large technique effect found in the trade and environment literature.

An empirical literature exists which estimates the effect of ownership on emissions or emissions intensity, using different data sets. As in our paper, most of these studies find that SOEs are more pollution intensive than private firms. Wang and Wheeler (2003) find that provinces in China with larger state owned sectors have higher emissions intensity. Wang and Jin (2007) find state owned plants in China are more emissions intensive than non-state owned plants. However, Wang and Wheeler (2005) find no significant difference in emissions intensity between state owned and non-state owned plants (although 93% of their sample is state owned). Pargal and Wheeler (1996) study biological oxygen demand in Indonesia and find that firms with a higher share of state owned equity are more pollution intensive. Hettige, Huq, and Pargal (1996) survey studies with similar results.⁷ Talukdar and Meisner (2001) consider CO₂ emissions for a panel of countries and find that countries with a higher share of GDP produced by the public sector have higher emissions.

In addition several studies find that SOEs in some countries are held to lower standards for environmental compliance. 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. However, Earnhart and Lizal (2006) find an inverse relationship between pollution intensity and percentage of state ownership among recently partially

⁷Most of these studies control only for broad industry fixed effects, it is possible that SOEs specialize in emissions intensive goods within an industry. Thus, these studies are suggestive, but not definitive.

privatized firms in the Czech Republic in their preferred model. The latter study focuses on a change in ownership, which does not necessarily imply a change in subsidies.⁸

In the next section, we develop a theory of pollution, subsidies, and trade, and in section 3 we derive intuitive theoretical conditions for which pollution falls following a decrease in subsidies. Section 4 develops a computational version of the model. Section 5 gives the computational results, section 6 considers various robustness checks, and section 7 concludes.

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 richer and more precise 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.⁹ 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, 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.¹⁰ 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 a firm cannot increase profits by taking into

⁸It 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.

⁹Some subsidized firms clearly have monopoly power. This assumption is discussed in section 7.

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

account that its decisions affects 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} (measured 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.¹¹

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.¹² Our theory is not based on differences in firm ownership, since whether households or SOEs 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:

$$\pi_P = \max_{K_P, L_P} q_D A_P F(K_P, L_P) - \hat{r} K_P - \hat{w} L_P. \quad (2.1)$$

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

$$r = \hat{r}/q_D = A_P F_k(K - K_G, 1 - L_G), \quad (2.2)$$

¹¹The latter two interpretations are more reasonable for developing countries. All three interpretations are consistent with households renting capital.

¹²For 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).

$$w = \hat{w}/q_D = A_P F_l(K - K_G, 1 - L_G). \quad (2.3)$$

The problem of a subsidized firm consists of maximizing profits subject to the minimum labor constraint. The labor constraint binds (subsidized firms hire more labor than is efficient) if and only if $\hat{w} > q_D A_G F_l(K_G, L_G)$. 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,¹³ which implies:

$$\pi_G = \max_{K_G} q_D A_G F(K_G, L_G) - (1 - s) \hat{r} K_G - \hat{w} L_G. \quad (2.4)$$

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

$$(1 - s) r = A_G F_k(K_G, L_G). \quad (2.5)$$

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

We can also show:

$$\frac{\partial K_G}{\partial s} > 0, \quad \frac{\partial r}{\partial s} > 0, \quad \frac{\partial w}{\partial s} > 0, \quad (2.6)$$

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

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

Thus changes in the subsidies change the the subsidized sector's share of capital, labor, and output, which drives many of the results of the paper. First, 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

¹³A 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 $(1 - s)^\alpha A_P > A_G$.

also fall. Second, although a fall in the labor requirement will cause labor to move from the subsidized sector to 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. The equation which governs the fraction of capital allocated to the subsidized sector is:

$$(1 - s) A_P F_k(K - K_G, 1 - L_G) = A_G F_k(K_G, L_G). \quad (2.9)$$

2.2 Households

2.2.1 Final Good

Households enjoy consumption of a final good C , which is a composite of the domestic produced good 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:

$$\max \sum_{t=0}^{\infty} \beta^t u(C_t). \quad (2.10)$$

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 final goods:¹⁴

$$Y_c = X_D^\mu M^{1-\mu}. \quad (2.11)$$

We can interpret μ as the share of domestic production consumed domestically. The composite good can also be used for investment. Each country specializes in one good.

¹⁴The 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 flows. 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.

Therefore, we are ruling out composition effects,¹⁵ and 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 resource constraint is:

$$Y_c = C + K' - (1 - \delta) K. \quad (2.12)$$

Households use an efficient mix of X_D and M to form the final good. Let q_c denote the world price of the final 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 input prices equal the marginal contribution of the inputs of the final good:

$$q_D = \mu q_c X_D^{\mu-1} M^{1-\mu}, \quad (2.13)$$

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

Hence price ratio equals the marginal rate of technical substitution:

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

2.2.2 Trade

We follow Cox and Harris's (1985) study on the Canadian economy and use an almost small open economy framework. In this framework, domestic and foreign goods are imperfect substitutes. The domestic country has some market power in the export market and prices of domestically produced goods are endogenous. The domestic country is a price taker in the import market, and the supply of imported goods is perfectly elastic at the exogenous world price.¹⁶

¹⁵Composition effects would be important if, for example, subsidy reductions disproportionately stimulate output in pollution intensive sectors. The computational section of the paper, sections 4-5, has multiple sectors and explores the significance of these composition effects.

¹⁶The almost small economy assumption is technically convenient, but also not unrealistic. For example, according to the World Development Indicators, in 1997 China's share of world merchandise imports was only 2.5%, whereas Canada's share was 3.5% and the US 16%. We consider China in 1997 in the computational

Let τ_F denote the world tariff on domestic production, then the foreign demand curve for domestically produced goods is:

$$X_F = \hat{D} (q_D (1 + \tau_F))^{\frac{-1}{1-\zeta}}. \quad (2.16)$$

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 $D \equiv \hat{D} (1 + \tau_F)^{\frac{-1}{1-\zeta}}$, then:

$$X_F = D q_D^{\frac{-1}{1-\zeta}}. \quad (2.17)$$

We assume capital markets are closed.¹⁷ Therefore, trade in goods must balance:

$$M = q_D X_F. \quad (2.18)$$

2.3 Government

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

$$s\hat{r}K_G + S = -\hat{T}R + TF. \quad (2.19)$$

It is straightforward to show that 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:

$$srK_G + (w - A_G F_l(K_G, L_G)) L_G = -TR + \frac{TF}{q_D}, \quad (2.20)$$

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

analysis (sections 4-5).

¹⁷If we instead assumed an almost small open economy with a fixed interest rate, then the equilibrium function $K_G(\cdot)$ is unchanged and subsidies will still cause the economy to over-accumulate capital since the demand for capital still rises.

2.4 Market Clearing

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

$$X_D + X_F = Y = Y_G + Y_P. \quad (2.21)$$

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

$$q_c Y_c = q_D Y + TF = \hat{r}K + \hat{w} + \hat{T}R, \quad (2.22)$$

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

2.5 Pollution

We assume emissions, E , of a flow pollutant are 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:

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

No abatement technology exists, so pollution falls only by reducing output or by moving production to the less pollution intensive sector.¹⁸ 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 function of aggregate output:

$$E = \sigma Y. \quad (2.25)$$

Here σ is the economy wide pollution intensity:

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

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 (2.15), (2.17), and

¹⁸We 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.

(2.18) imply the domestic demand curve is:

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

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:

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

Hence:

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

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

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

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

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 resource constraint implies:

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

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

$$\phi \equiv \mu + \zeta (1 - \mu). \quad (3.9)$$

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 final 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:

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

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:

$$u_c(C(K; s; L_G)) = \beta v_k(K', K') \quad (3.11)$$

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

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

$$Y(K; s; L_G) = A_P F(K - K_G(K; s; L_G), 1 - L_G) + A_G F(K_G(K; s; L_G), L_G) \quad (3.14)$$

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 $w > srK_G(K) + S(K)$ for all K . 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 (3.11) and (3.12), and
4. $H(K)$ 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.¹⁹

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 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:

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

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

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

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

$$\frac{\sigma_G}{\sigma_P} > \frac{1}{1 - s}. \quad (3.17)$$

¹⁹For Cobb-Douglas production with capital share α , $s < (1 - \alpha)/\alpha$ is sufficient.

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 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 $(\bar{\bar{K}}, \bar{\bar{E}})$ with $\bar{\bar{K}} < \bar{K}$. Further, $\bar{\bar{E}} < \bar{E}$ if and only if:*

$$\frac{\sigma_G}{\sigma_P} > \frac{(1-\phi)\theta_P}{(1-\phi)\theta_P + \alpha_P}, \quad \theta_i \equiv \frac{\hat{r}\bar{K}_i}{\bar{Y}}, \quad \alpha_i \equiv \frac{-F_{KK}\left(\frac{\bar{K}_i}{L_i}, 1\right)K_i}{F_K\left(\frac{\bar{K}_i}{L_i}, 1\right)L_i}, \quad i = G, P \quad (3.18)$$

Furthermore, if condition (3.17) also holds, then:

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

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 condition (3.18) holds, then, following a decrease in interest subsidies, initially pollution rises but subsequently falls to a lower steady state. Condition (3.18) is easily checked since θ_P is the share of income accruing to the private capital owners and α_P measures the curvature

of the production function. Note that a sufficient condition for condition (3.18) is $\sigma_G > \sigma_P$. Therefore, steady state pollution falls with a decrease in interest subsidies if the subsidized sector is more pollution intensive than the private sector, as is commonly found in the literature (e.g. Wang and Jin 2007).

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

$$\frac{\partial E}{\partial s} = \frac{\partial \sigma}{\partial s} Y + \sigma \frac{\partial Y}{\partial s}. \quad (3.19)$$

After simplifying, we obtain:

$$\frac{\partial E}{\partial s} = (\sigma_G - \sigma_P) \frac{\partial K_G r(K) \left((1-s) Y^P + Y^G \right)}{\partial s Y} - s \sigma \frac{\partial K_G r(K)}{\partial s}. \quad (3.20)$$

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 interest subsidies.

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 $K_0 = \bar{K}$.*

1. *Pollution transitions to a new steady state $\bar{\bar{E}}$ with $\bar{\bar{E}} < \bar{E}$ if and only if:*

$$\frac{\sigma_G}{\sigma_P} > \frac{(1-\phi)(\Gamma_G \theta_P + \Gamma_P \theta_G) + \alpha_P \alpha_G \Gamma_P}{(1-\phi)(\Gamma_G \theta_P + \Gamma_P \theta_G) + \alpha_P \alpha_G \Gamma_G}, \quad \Gamma_i \equiv \frac{Y_i}{L_i} \quad (3.21)$$

Further, if conditions (3.17) and (2.8) hold, then:

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

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, if private firms are less pollution intensive, pollution tends to fall when labor moves from subsidized to private firms. Condition (2.8) implies $1/(1-s)$ 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 (condition 3.21).

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

$$\frac{\sigma_G}{\sigma_P} > \left(\frac{A_P (1-s)^\alpha}{A_G} \right)^{\frac{1}{1-\alpha}}. \quad (3.22)$$

In the calibration, condition (3.22) 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 $(\bar{\bar{K}}, \bar{\bar{E}})$ 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 capital.

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

In this section we use a dynamic applied general equilibrium model (AGE) in order to assess the effect of changes in tariffs and direct and interest subsidies on pollution emissions. We calibrate the model to match data in the Chinese input-output (I/O) matrix for 1997. In order to make quantitative predictions, the computational model adds several features not present in the theoretical model.²⁰ First, we assume the population L grows at exogenous rate n , and that A_G and A_P grow at exogenous rate $\gamma^{1-\alpha} - 1$, where $\gamma - 1$ is the growth rate of labor augmenting technical change.

One private firm and one SOE co-exist in each of $j = 1 \dots J$ traded sectors. Production in each sector requires capital, labor, and intermediate inputs. Let z_{hji} denote use of intermediate input i in production of good j , where $h \in \{G, P\}$ indicates ownership type. Then domestic production is:

$$Y_{hj} = F(z_{hj1}, \dots, z_{hjJ}, K_{hj}, L_{hj}) = \min \left\{ \frac{z_{hj1}}{a_{j1}}, \dots, \frac{z_{hjJ}}{a_{jJ}}, A_{hj} K_{hj}^{\alpha_j} l_{hj}^{1-\alpha_j} \right\}. \quad (4.1)$$

Here Y_{hj} denotes gross domestic output, and a_{ji} are productivity parameters for intermediate inputs. Let $X_{Dj} = Y_{Gj} + Y_{Pj}$ denote aggregate gross domestic output. For technical simplicity we assume production is Leontief in intermediate inputs.

We generalize the Armington aggregator in the production of the final good to be CES:

$$Y_{cj} = A_{Mj} \cdot \left(\mu_j X_{Dj}^{\zeta_j} + (1 - \mu_j) M_j^{\zeta_j} \right)^{\frac{1}{\zeta_j}}. \quad (4.2)$$

Here $\frac{1}{1-\zeta_j}$ is the elasticity of substitution between the domestic and foreign produced goods, A_{Mj} is a productivity parameter, and μ_j reflects the importance of the domestic good in production of final goods.

A combination of final goods produces an investment good and a composite consumption good. We assume a Cobb-Douglas investment production function, with share parameter ν_j :

$$I = A_I \prod_{j=1}^J \frac{I_j^{\nu_j}}{\nu_j}. \quad (4.3)$$

²⁰None of these features are critical for our qualitative analysis of the effect of subsidies on pollution and, therefore, the intuition from the theoretical model applies to the quantitative model.

The composite consumption good is a CES aggregate of final goods:

$$\hat{C} = \left(\sum_{j=1}^J \epsilon_j C_j^\rho \right)^{\frac{1}{\rho}}. \quad (4.4)$$

Here C_j is consumption of final good j . The period utility function which represents household preferences is:

$$u(\hat{C}) = \frac{\hat{C}^\chi - 1}{\chi}. \quad (4.5)$$

The price for investment goods (q_I) and the composite consumption good (q_C) now differ, so the household budget constraint becomes:

$$q_{Ct}\hat{C}_t + q_{It}(K_{t+1} - (1 - \delta)K_t) = \hat{w}_t L_t + \hat{r}_t K_t + \hat{T}R_t. \quad (4.6)$$

The computational model adds exogenous government purchases per capita, G , and taxes on gross domestic output, T , which better matches China's revenue sources. The government budget constraint is now:

$$\sum_{j=1}^J (q_{Cj}G_j + s_j \hat{r} K_{Gj} + S_j) + \hat{T}R = TF + T. \quad (4.7)$$

Here production tax and tariff revenues are:

$$T = \sum_{j=1}^J t_j q_{Dj} X_{Dj}, \quad (4.8)$$

$$TF = \sum_{j=1}^J \tau_{Dj} M_j, \quad (4.9)$$

The government budget constraint remains balanced with a lump sum transfer. Section (6.3) considers an alternative assumption that the government constraint is balanced by adjusting the production tax rate.

For the market clearing equations, balanced trade implies:

$$\sum_{j=1}^J M_j = \sum_{j=1}^J q_{Dj} X_{Fj}, \quad (4.10)$$

We assume the foreign demand parameter D_j also grows at rate $\gamma - 1$, which is consistent

with the existence of a balanced growth path. Therefore exports are:

$$X_{Fj} = D_j q_{Dj}^{\frac{-1}{1-\zeta_j}}, \quad j = 1 \dots J. \quad (4.11)$$

Demand equals supply in the final goods, labor, and capital markets:

$$C_j + I_j + G_j + X_{Fj} + \sum_{i=1}^J (z_{Pij} + z_{Gij}) = Y_{cj}, \quad j = 1 \dots J, \quad (4.12)$$

$$\sum_{j=1}^J (L_{Gj} + L_{Pj}) = L, \quad (4.13)$$

$$\sum_{j=1}^J (K_{Gj} + K_{Pj}) = K. \quad (4.14)$$

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

$$E = \frac{1}{EI} \sum_{j=1}^J (\sigma_{Gj} Y_{Gj} + \sigma_{Pj} Y_{Pj}). \quad (4.15)$$

Here EI grows exogenously at rate $\gamma - 1$, which is consistent with a stationary level of pollution emissions. All other assumptions are the same as the theoretical model.

5 Simulation Results

We calibrate the computational model to match Chinese economic and environmental data for 1997 (details are in appendix B and Tables 1-3 give the parameter values).²¹ Following common practice in trade agreements, we implement policy changes over a five year reform period. We take 1997 as the initial year and 2000-4 as the reform period.

The Chinese economy was not in a steady state in 1997. Therefore, to isolate the effects of the changes in subsidies from changes resulting from development, we present all results relative to a benchmark economy, which assumes no policy changes.²²

²¹The 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 critical emissions intensity parameters.

²²In the benchmark economy, initial capital is 64% of steady state capital, and converges to within 0.1% of the steady state in 47 years.

Although the policy changes are not fully implemented until 2004, in anticipation of the new policies, households change decisions beginning in 1997. Since pollution is proportional to output, pollution also changes in anticipation of the policy changes. 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. Pollution data is available for three air pollutants: SO₂, soot, and industrial dust (see appendix B.2 for details). Soot refers to emission of particulate matter from industrial fuel combustion, and industrial dust is emission of particulates from industrial processes.

We consider a benchmark scenario and four policy experiments. The benchmark scenario, assumes no changes in any policy variables. In the four policy experiments, policies change gradually over the reform period.

The first experiment gradually reduces direct subsidies by 5% over the reform period. In our framework, reducing direct subsidies requires a relaxation of the minimum labor requirement. Reducing the required minimum labor moves labor to the private sector, which increases the marginal product of capital in the private sector. Therefore, capital also moves to the private sector. Table 6 shows both of these effects raise steady state aggregate output to 2.36% above the benchmark scenario. 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 6 and Figures 1-3, steady state pollution falls relative to the benchmark for all three pollutants, from a decrease of 1.78% in soot to a 11.62% decrease in dust.

Figures 1-3 show the dynamic path of pollution. Prior to the reform period, a small rise in SO₂ and soot occurs as compositional effects outweigh a small negative scale effect. Figure 4 shows the time path of aggregate output, which is the scale effect. Households anticipate income will rise after the reform period, and smooth consumption by reducing investment in the pre-reform period, reducing capital (see Figure 5) and output. Pollution decreases during the reform period. Figure 4 shows that aggregate output is increasing during the reform period, as reallocating inputs to the more productive private sector more than offsets the decline in the capital stock. This scale effect is smaller than the technique effect which are the reallocation effects resulting from moving labor and capital to the less pollution intensive sector. The resource reallocation effect is in accordance with the prediction of Theorem 3, since the output weighted average of σ_G/σ_P exceeds the capital-weighted average $1/(1-s) = 2.22$ for all three pollutants. Pollution relative to benchmark after 2004 increases

only slightly, so the capital accumulation effect is small here (see Figure 5). Overall, SOEs are sufficiently more pollution intensive in our calibrated model for the technique effect to outweigh the scale effect.

Table 7 breaks down the steady state change in pollution into scale, technique, and composition effects.²³ The scale effect is positive for the decrease in direct subsidies, and equal to the percentage change in aggregate output. The scale effect is identical across pollutants, since aggregate output is independent of pollution. The technique effect is the largest effect for all pollutants. Antweiler, Copeland, and Taylor (2001) find a relatively strong technique effect which they attribute to demand for environmental quality rising with income. Our results show that reducing direct subsidies can also generate large technique effects.

Composition effects are small. Our model allows for sectoral differences in the use of intermediate inputs, pollution intensity, TFP, size of subsidies, and other parameters (see Tables 2-3). However, parameters that affect the distribution of demand for goods across sectors (for example ϵ_j and a_{ji}) do not change from the benchmark. The primary reason for small composition effects is that intersectoral changes in pollution go in different directions and tend to cancel out. Some intersectoral reallocations are from low to high emission sectors, but others go in the opposite direction. In contrast, since in all sectors subsidized firms are more emissions intensive than private firms, the technique effect goes in the same direction for all sectors. This can be seen from equation (C.5), which shows that the composition effect is the sum of many terms of ambiguous sign, whereas the technique effect is a single aggregate term. Finally, all tariff and subsidy reductions are uniform percentage reductions across sectors. Reducing subsidies or tariffs unevenly across sectors may result in larger composition effects.

The second policy 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. Preventing SOE losses, and therefore direct subsidies, from increasing requires also a 2.4% reduction in the labor requirement over the reform period. Although interest subsidies are not typically marked for elimination in trade treaties, they are prohibited for example under WTO rules. The reduction in the interest subsidy rate lowers the overall return to capital and causes existing capital to flow to the private sector. Table 6 shows the resulting fall in investment lowers steady state aggregate output only slightly (0.01%) relative to the benchmark scenario. The steady state scale effect therefore reduces pollution here. Production

²³Appendix C derives the scale, technique, and composition effects for the computational model.

also moves to the less pollution intensive private sector, further reducing pollution. Thus the scale and technique effects both result in a decrease in steady state pollution. Table 7 shows that the technique effect is also relatively large (a 2% reduction in the interest subsidy rate generates a technique effect equal to a 1.63% decrease in soot to a 5.2% decrease for dust).

Figures 1-3 give the dynamic path of pollution following the reduction in interest subsidies. As with the decrease in direct subsidies, the capital accumulation effect is small. Pollution does fall slightly for all pollutants however, subsequent to 2004. The reduction in the interest subsidies reduces the incentive to accumulate capital, so capital and aggregate output fall from 2004 onward (Figures 4-5), causing a reduction in all pollutants. In contrast, in the first experiment, reducing direct subsidies caused more capital to move to the more productive private sector, causing capital and aggregate output to rise after 2004, increasing pollution slightly.

The third policy experiment combines the two changes in policies. It shows the effect of a 2% reduction in the interest subsidy rate, together with an additional 5% decrease in direct subsidies in the reform period. The model requires an 11.45% reduction in the labor requirement to keep direct subsidies at the target of 5% below benchmark. As a result of the combined policy changes, the fall in pollution is larger (see Table 6 and Figures 1-3). Long run aggregate output increases, since the lower return to capital caused by lower subsidies is offset by labor moving to the high productivity private sector, increasing aggregate output. The reductions in pollution range from 3.13% for soot to 16.47% for dust.

The fourth policy experiment analyzes the effect of a pure tariff reduction. In particular, we eliminate the rest of the world's tariffs (from the calibrated 5% to zero) against China. This causes an increase in demand for Chinese goods and a corresponding increase in aggregate output. As shown in Table 6 and Figures 1-3, pollution rises over time as the higher demand for Chinese products increases the return to capital and the economy grows. Pollution increases from 0.87% for SO₂ to 1.45% for dust. From Table 7, the technique effect is nearly zero, as expected. Reducing tariffs does not create any particular incentive to move production from SOEs to private firms, which is the only technique effect in the model. Composition effects are small with the exception of dust. Overall, pollution has a more elastic response from a decrease in subsidies than from a decrease in tariffs, due to the technique effect.

Table 6 shows the changes in the steady state terms of trade for each simulation. For the first experiment, steady state terms of trade worsen by 0.71%. Since condition (2.8) holds in aggregate, steady state output rises, and the excess supply of goods on the world market

depresses the export price. The lower export price moderates the desire to accumulate capital (steady state capital decreases by 1.27% relative to benchmark), reducing the scale effect. Interestingly, the reduction in interest subsidies has the opposite effect. Steady state production falls with interest subsidies, which improves terms of trade. But since the fall in output is small, so is the change in terms of trade. Clearly steady state terms of trade improves in the fourth experiment, as the tax on Chinese exports falls.

6 Sensitivity Analysis and extensions

6.1 Emissions intensity uncertainty

In this section we perform sensitivity analysis on the difference between σ_G and σ_P , which is estimated from panel data on emissions intensity and SOE shares. Our preferred econometric model is a fixed effects specification with a time trend (model 3 Tables 4-5, see appendix B.4 for details). The key coefficient is $\hat{\eta}_1 = \sigma_G - \sigma_P$. Here, we run again the simulations in section 5 changing $\hat{\eta}_1$ in two different ways. First, we reduce $\hat{\eta}_1$ by one standard deviation. Second, we use the values of $\hat{\eta}_1$ estimated in an alternative regression model with year specific effects (model 4 in Tables 4-5).

Table 8 indicates the long run pollution still decreases for all experiments that reduce subsidies, except for reducing $\hat{\eta}_1$ for soot by one standard deviation for soot in experiment 1. Comparing Tables 6 and 8, we see that the effect of reducing subsidies on SO₂ falls by 33-57% when $\hat{\eta}_1$ is reduced by one standard deviation. The largest reduction is for soot (54% to 110%), the pollutant for which $\hat{\eta}_1$ had the most variance. Dust emissions relative to benchmark actually increases by 11-15%, since reducing σ_G reduces both benchmark emissions and emissions when subsidies are reduced. For dust, the reduction in benchmark emissions is larger so emissions relative to benchmark rise. Using σ_G from model 4 reduces the effect of reducing subsidies by 8-10% for SO₂, by 14-15% for soot, and by 29-35% for dust, but the reducing subsidies still reduces pollution for all experiments and pollutants.

In the experiment where only tariffs are reduced, the results are virtually unchanged for all pollutants, except for dust (31% larger after reducing $\hat{\eta}_1$, and 16% smaller using model 4). This is not surprising, given that for this experiment technique and composition effects are small (except for the composition effect in dust). Overall we conclude that the qualitative results are robust to reasonable changes in the ratio of emissions intensities. The effect on the magnitude of the results depends on the pollutant and experiment.

6.2 The effect of the productivity differential

Our calibration implies the output weighted average TFP of private firms is 86% higher than SOEs. Here we reduce the ratio $\frac{A_P}{A_G}$ by half, by reducing A_{Pj} evenly across sectors. If private and SOEs have more similar productivity, then SOEs will produce a larger share of aggregate output. However, this affects the benchmark as well as the other experiments. When subsidies are reduced, if the TFP differential is small, then less capital and labor will move from SOEs to private firms. This reduces both the scale effect (aggregate output growth is less because private firms are not as productive), and the technique effect (SOEs account for a larger fraction of aggregate output). The overall effect is therefore ambiguous.

Table 8 shows the magnitude of steady state reduction in pollution relative to benchmark rises for all experiments for SO₂ and soot, but falls for the dust experiments. Thus, the smaller scale effect dominates for SO₂ and soot, but the smaller technique effect dominates for dust. This makes sense since dust had the largest technique effect to start with, and all three pollutants have the same scale effect. The tariff experiment is virtually unchanged when $\frac{A_P}{A_G}$ falls.

6.3 The effect of distortionary production taxes

In section 5, we assumed smaller government subsidies resulted in smaller lump sum taxes in the government budget constraint. This isolates the effect of subsidy reductions on emissions. However, if instead the government used the revenue freed up by reducing subsidies to reduce distortionary production taxes, then the scale effect would increase. Lower production taxes raise steady state aggregate output, and therefore pollution. Here we quantify whether this additional scale effect is enough to cause pollution to rise following a reduction in subsidies.

The changes in subsidies are phased in, and the economy is on the transition path to the steady state. Therefore, the governments fiscal position varies over the transition path. To make the experiment straightforward, we set the production tax rate in all periods so that the economy with less subsidies and lower production taxes converges to a steady state with an identical transfer as the steady state of the benchmark economy.

The required reduction in production taxes is 13.49%, 5.97%, and 18.99%, for experiments 1-3, respectively. Table 8 shows that the stronger scale effect means pollution falls by less when subsidies are reduced. The magnitude of steady state pollution relative to benchmark falls by 8-57%, depending on the experiment and pollutant, but pollution still falls relative to benchmark for all pollutants and experiments that reduce subsidies.

7 Conclusions

In this paper, we analyze the effects of perverse subsidies and trade policy on the environment. We give theoretical conditions for which a reduction in subsidies to industry results in a decrease in pollution. The 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, after controlling for industry fixed effects, SOEs are significantly more pollution intensive than private firms for three of four pollutants studied. Furthermore, our computational section shows that reducing direct subsidies to Chinese SOEs reduces pollution for SO₂, soot, and dust. Reducing subsidies has a more elastic response than reducing tariffs. Direct and interest subsidies are larger to begin with, and interest subsidies directly affect capital accumulation, resulting in both the scale and technique effects lowering pollution.

Several caveats are in order. First, given that China's state owned sector comprises about 46% of industry value added, China represents an extreme case. Still, given the evidence of weak enforcement of environmental regulations on SOEs in countries like India and Indonesia, and the prevalence of SOEs in developing countries, our analysis 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 in our model are price takers. Subsidized firms may have monopoly powers and SOEs 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, for the case of China, SOE shares of value added are reasonable,²⁴ which supports the idea that SOEs and private firms compete in the same industries at least for China.

We are ignoring some other policies which cause deviations from the competitive equilibrium, such as other subsidies and price controls.²⁵ In appendix B.3, we use emissions per unit of value added as emissions intensity and SOE value added divided by aggregate value added rather than the ideal emissions per unit of production and SOE production divided by

²⁴Five of 9 industries considered have SOE shares of value added less than 50%, and the maximum is 81%.

²⁵Young (2000) views price controls as inter-regional tariffs, which we do not consider since our model is not disaggregated by region. Price controls specific to SOEs could be implemented, but we lack price data by ownership.

aggregate production. If SOEs are subject to price controls, a one to one mapping between value added and production no longer exists.

We assume subsidies are reduced by an equal percentage across sectors. If subsidies are reduced unevenly, stronger composition effects may result. Finally, we use the Armington aggregator specification to capture intra-industry trade. It is well known that AGE models using this specification underestimate the magnitude of the increase in trade following a reduction in tariffs, even though they predict quite well which sectors will be most affected.

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. A trade agreement may 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 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.

A Appendix: Proofs of theorems

This material is available at the *Journal of Environmental Economics and Management's* online archive of supplementary material.

B Appendix: Data and Calibration

B.1 Economic Data and Parameters

The calibration matches data from the Chinese National Income and Product Accounts, the Chinese I/O matrix, and the SOEs shares for labor, capital, and output in Chinese industry for 1997. The source for all economic data is the *China Statistical Yearbook* (CSY), with the exception of the SOE shares for labor where the source is the *China Labor Statistical Yearbook* (CLSY).

The I/O data has 17 sectors, but we consider only the 10 industry sectors, since data on emissions for services, construction and agriculture are not available. We exclude the sector foodstuff (including food processing and manufacturing, beverages, and tobacco), since our calibrated parameter values imply SOEs are only slightly less productive than private firms in the foodstuff industry, which implies a very small share of steady state private foodstuff production that is difficult to solve for numerically.²⁶ This leaves nine usable sectors: mining, textiles, other manufacturing, electric power/utilities, coking and petroleum refining, chemical industry, non-metal mineral products, metal products, and machinery and equipment. The nine sector aggregation in the I/O data is not ideal from an environmental perspective, as many industries with different emissions profiles are grouped together, but this is the most disaggregated data available. The calibration of the economic parameters follows standard procedures in AGE models. Tables 1-3 report the calibrated parameter values.

The tax rates match the fraction of gross domestic output paid in taxes in the data:

$$t_j = \frac{\text{taxes paid}_j}{X_{Dj}}. \quad (\text{B.1})$$

Optimal use of intermediate inputs implies the intermediate input productivity parameters are:

$$a_{ji} = \frac{z_{ji}}{X_{Dj}}. \quad (\text{B.2})$$

Therefore, a_{ji} matches the fraction of intermediate inputs to output in the I/O matrix. The capital share α_j matches the fraction of private income accruing to private capital owners:²⁷

$$\alpha_j = \frac{rK_{Pj}}{Y_{Pj}(1 - t_j - \sum_i a_{ji})}. \quad (\text{B.3})$$

²⁶One possibility is that within the foodstuff sector private firms are too small to take advantage of economies of scale. The larger SOEs then become more productive. Foodstuff accounts for less than four percent of emissions for each air pollutant.

²⁷Private capital income consists of operating surplus and depreciation of fixed assets. The data considers sole proprietorship income as labor compensation, which we cannot disaggregate into labor and capital income. Minghai, Wen, and Xianguo (2010) estimate that the economy wide (here we use only private capital income in industrial sectors) α rises by 3-5% when proprietorship income is split between labor and capital.

Given the capital share, calibrated private and SOE TFP parameters (A_{Pj} and A_{Gj}) solve:

$$A_{hj} = \frac{Y_{hj}}{K_{hj}^{\alpha_j} L_{hj}^{1-\alpha_j}} \quad j = 1 \dots J, \quad h = \{G, P\}. \quad (\text{B.4})$$

Optimal use of inputs implies the investment share parameter, ν_j , matches the ratio of final good j used in production of investment goods to total investment in the data:

$$\nu_j = \frac{I_j}{I}, \quad j = 1 \dots J. \quad (\text{B.5})$$

We set $\zeta_j = \zeta_{Fj} = 0.5$. Tiwari, et. al. (2002) estimates $\tau_{Dj} = 0.02$ and $\tau_{Fj} = 0.052$, $j = 1 \dots J$. We then choose μ_j to match the ratio of domestic consumption to imports in the data:

$$\mu_j = \left(1 + \frac{M_j}{X_{Dj}} (1 + \tau_{Dj}) \right)^{-1}. \quad (\text{B.6})$$

Given μ_j , A_{Mj} may be calibrated from equation (4.2). The foreign demand parameter D_j is calibrated from equation (4.11).

We set $\rho = -1$, which is within the range of values used in the real business cycle (RBC) literature. Household optimization then implies ϵ_j is the weight households place on consumption good j relative to other consumption goods.

$$\epsilon_j = \left(\frac{C_j}{C_1} \right)^{\rho-1} \left(\sum_{i=1}^J \left(\frac{C_i}{C_1} \right)^{\rho-1} \right)^{-1}. \quad (\text{B.7})$$

The most critical economic parameters are the interest subsidy rate and the labor constraint. The firm first order conditions imply:

$$s_j = 1 - \frac{K_{Pj} Y_{Gj}}{K_{Gj} Y_{Pj}}. \quad (\text{B.8})$$

The calibration sets the interest subsidy rate so that the difference in the capital to output ratios between private firms and SOEs in the model matches the data. SOEs used 65% of the capital, but produced only 36% of gross domestic output in the nine sectors considered for 1997. To explain the high capital to output ratio of SOEs, the model calibration requires a capital-weighted average interest subsidy rate of 0.49.²⁸

²⁸In our calibration the 65% of capital owned by SOEs receive a subsidy of 0.49, for an economy wide average subsidy of 0.32. Our subsidy rate is lower than the value calibrated by Fisher-Vanden and Ho (2007), using a different methodology. They report 53% of the capital stock (“plan capital”) received a subsidy of 0.9 in 1995, for an economy wide average subsidy of 0.48.

We calibrate the minimum labor requirement using the fraction of total wages which go to SOEs workers.²⁹

B.2 Emissions Data

For the critical emissions intensity parameters, national and industry level emissions data is available for four pollutants, but SOE emissions are not reported separately. However, industry emissions and SOE industry shares are available, which allows us to estimate the aggregate SOE pollution intensity using industry data.

We gathered industry emissions data for air pollutants SO₂, soot, and industrial dust and for the water pollutant COD from various editions of the *China Environment Yearbook* (1996-2008 covering years 1995-2007). Industry air pollutant emissions data for the same pollutants and period are also available from various editions of the *Chinese Statistical Yearbook* (hereafter CSY). 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 which accounts for 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.

The CSY reports nominal value added by industry for 1995-2007 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 industry shares of aggregate value added.³⁰ 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

²⁹A one sector model which calibrates L_G to match subsidies to loss making SOEs produces quantitatively similar results. SOE loss data cannot be used to calibrate L_{Gj} since SOE loss data is unavailable by sector. SOEs may sometimes subject to price controls (Young 2000), especially for consumer goods, which is an alternative reason for SOE losses. Imposing price controls on SOEs requires separate output price data for SOEs and private firms, which is not available. Income from sole proprietorships is not included in the minimum labor requirement.

³⁰Industry data is more disaggregated than I/O data. We estimate emissions intensities using the disaggregated data and then aggregate the results to match the I/O data.

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 reported 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. Two issues arise when using these price deflators. First, GOV is a measure of revenue, not value added. Second, firms directly report real GOV data. Young (2003) questions the accuracy of the implicit price deflators derived from reported data. The *CSY* (2006-7) reports ex-factory (producer) price indices of industrial products derived independently from the reporting firms for the years 2002-2007, using 2001 as the base year. We use the Holz data until 2001 and the ex-factory price indices for 2002-2007, which results in the largest data set. The results are similar regardless of the deflator used for 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 compatible with the 1995-2000 emissions data, since Holz's data uses the 1994 classification system.

Later industry classifications are more disaggregated, although most 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 we exclude, since we cannot convert the price data to 1990 dollars. Three industries which begin in 2001 end in 2002 (two are discontinued and one is missing deflator data). The emissions data include a few industry categories not available in the output data (such as cement). We cannot use these industries since SOE share data does not include these categories. Hence we have a panel of 41 industries, some of which begin in 2001 or end in 2002.³¹

In total, we have 296 observations, an unbalanced panel of 41 industry classifications over 10 years.

³¹Controlling for industry fixed effects using more aggregate industry classifications in general produced poor results, since aggregate classifications include both low and high emission industries.

B.3 Industry level calibration: estimation strategy

Applying equation (2.26) to industry j gives:

$$\frac{E_{jt}}{Y_{jt}} \equiv \frac{E_{Pjt}}{Y_{jt}} + \frac{E_{Gjt}}{Y_{jt}}. \quad (\text{B.9})$$

Let $v_{jt} \equiv \frac{Y_{Gjt}}{Y_{jt}}$ denote the SOE share in industry j , then:

$$\sigma_{jt} \equiv \sigma_{Pjt} (1 - v_{jt}) + \sigma_{Gjt} v_{jt}, \quad (\text{B.10})$$

$$\equiv \sigma_{Pjt} + (\sigma_{Gjt} - \sigma_{Pjt}) v_{jt}. \quad (\text{B.11})$$

Equation (B.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 fixed effects terms, terms in which industry terms 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 296 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:

$$(\sigma_{Gjt} - \sigma_{Pjt}) = \eta_1 + \eta_2 \cdot 1(t > 1998) + \xi_{1jt}, \quad \xi_{1jt} \sim \text{iid mean } 0. \quad (\text{B.12})$$

Here $\eta_1 = (\sigma_G - \sigma_P)_{t < 1998}$ is the parameter of interest, while $\eta_1 + \eta_2$ measures the slope after 1998. For the constant term, we employ a fixed effects specification:

$$\sigma_{Pjt} = \sigma_{Pj} + Q(\eta, t) + \xi_{2jt}, \quad \xi_{2jt} \sim \text{iid mean } 0. \quad (\text{B.13})$$

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:

$$\sigma_{jt} = \eta_{0j} + \eta_1 v_{jt} + \eta_2 v_{jt} 1(t > 1998) + Q(\eta, t) + \xi_{jt}, \quad (\text{B.14})$$

$$\xi_{jt} = \xi_{1jt}v_{jt} + \xi_{2jt}. \tag{B.15}$$

According to specification (B.14), the errors will be heteroskedastic. We will consider for Q a simple time trend and year specific effects.

We normalize Q so that $Q(\eta, 1997) = 0$. Then, given estimated coefficients $\hat{\eta}_{0i}$ and $\hat{\eta}_1$, estimated emissions intensities are:

$$\sigma_{Pj} = \hat{\eta}_{0j}, \tag{B.16}$$

$$\sigma_{Gj} = \sigma_{Pj} + \hat{\eta}_1. \tag{B.17}$$

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

B.4 Estimation Results

In addition to estimating (B.14) using fixed effects, we tried several variations of the model to check for robustness. We find that the results are not sensitive to the mixture of price deflators used, and the significance of the key coefficient η_1 is not sensitive to using alternative output measures. Although not consistent with the theory developed in section 2, we tried a log specification. The sign of η_1 remains positive for all regressions but gains significance for COD and loses significance for SO₂. Controlling for the industry share of output results in a smaller coefficient for soot, but adds virtually no explanatory power to the regression. The results are sensitive to the introduction of a time trend or time specific effects. Thus we report the results for industry fixed effects, with and without a time trend and time specific effects.

Tables 4-5 report the estimation results for OLS, industry fixed effects, industry fixed effects including a time trend (our preferred model), and industry fixed effects with year fixed effects. All t-statistics are calculated using standard errors corrected for heteroskedasticity using the White procedure.³²

³²Stock 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

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 in column 2 requires the economy wide σ_P to be negative for COD.

One explanation 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 specific effects (column 4) are added, $\hat{\eta}_1$ remains positive but loses significance for COD (soot is significantly positive using a one sided test at the 95% level).³³ 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 year coefficients are significant for any pollutant), but $\hat{\eta}_1$ is in its theoretical range. Apparently, for COD, the data does not have enough within-industry, within-year variation to pin down $\hat{\eta}_1$ very precisely.

For calibration and simulation purposes, we use regression (3). Table 9 gives the calibrated emissions intensities. In the sensitivity analysis section, we vary $\hat{\eta}_1$ to account for the uncertainty of the estimate and alternative regression specifications. We omit COD from the simulations since the estimate for COD is very imprecise.

Our regression results generally imply SOEs are much more emissions intensive than private firms. Computing the economy wide σ_G/σ_P for the time trend regression, we see that SOEs are 5 times more emissions intensive for SO₂, 3.8 times more emissions intensive for soot, and 9.3 times more emissions intensive for dust, while the difference in emissions intensity is not significant for COD. These results are broadly consistent with the existing literature. In particular, our specification is most similar to Wang and Wheeler (2003), who use a province level panel data set from 1987-1995 in China to estimate a model in which pollution charges and COD emissions intensity are jointly determined, controlling for the share of output produced from each sector in the province. Their results indicate a province with only state owned firms would be 5.7 times as emissions intensive as a province consisting

periods. Discarding the data with two time periods and using their correction did not materially alter the results.

³³We tried other empirical specifications of the time trend and obtained similar results.

of only private firms. Wang and Jin (2007) conducted a survey of 842 plants in China in 2000. After controlling for industry fixed effects, they find for total suspended solids that state owned firms are more than twice as emissions intensive as non-state owned firms. Pargal and Wheeler (1996) find for biological oxygen demand in Indonesia that a 100% government owned firm is 18 times more pollution intensive than a 100% privately owned firm, after controlling for industry effects and other factors.³⁴ However, Wang and Wheeler (2005) use a survey of 3000 plants in China in 1993 to estimate a model of endogenous pollution charges and emissions for a variety of air and water pollutants. They find no significant difference between emissions of SOEs and private firms, although 93% of their sample is state-owned.

C Appendix: Derivation of scale, technique, and composition effects

From the definition of emissions intensity, we have:

$$E = \sum_{j=1}^J \sigma_{Gj} Y_{Gj} + \sum_{j=1}^J \sigma_{Pj} Y_{Pj}, \quad (\text{C.1})$$

$$= \sum_{j=1}^J \sigma_{Gj} \left(\frac{Y_{Gj}}{Y_G} \right) \left(\frac{Y_G}{Y} \right) Y + \sum_{j=1}^J \sigma_{Pj} \left(\frac{Y_{Pj}}{Y_P} \right) \left(\frac{Y_P}{Y} \right) Y. \quad (\text{C.2})$$

$$= \sum_{j=1}^J \sigma_{Gj} v_{Gj} v_G Y + \sum_{j=1}^J \sigma_{Pj} v_{Pj} (1 - v_G) Y. \quad (\text{C.3})$$

Here v_{Gj} and v_G are industry share of SOE production and the economy wide SOE share, respectively. Totally differentiating gives:

$$\begin{aligned} \dot{E} = & \dot{Y} \frac{E}{Y} + \frac{\dot{v}_G}{v_G} \left[\sum_{j=1}^J \sigma_{Gj} v_{Gj} v_G Y - \sum_{j=1}^J \sigma_{Pj} v_{Pj} v_G Y \right] + \\ & \sum_{j=1}^J \left[\frac{\dot{v}_{Gj}}{v_{Gj}} \sigma_{Gj} v_{Gj} v_G Y + \frac{\dot{v}_{Pj}}{v_{Pj}} \sigma_{Pj} v_{Pj} (1 - v_G) Y \right]. \end{aligned} \quad (\text{C.4})$$

³⁴All three papers use a log specification $\log(\sigma_i) = \eta x_i + \eta_1 s_i + \zeta_i$, where x_i is a vector of covariates, η are the estimated parameters, s_i is either the SOE share of output or a dummy for state ownership, ζ is a random variable, and i indexes plants or provinces. We thus compute the ratio as: $\frac{\sigma_G}{\sigma_P} = \frac{\exp(\eta x_i + \eta_1 + \zeta_i)}{\exp(\eta x_i + \zeta_i)} = \exp(\eta_1)$. Note, however, that the comparison is not exact since (in addition to differences in covariates and data sets) the mean emissions intensity ratio does not exactly equal the aggregate emissions intensity ratio.

Simplifying results in:

$$\frac{\dot{E}}{E} = \frac{\dot{Y}}{Y} + \frac{\dot{v}_G}{v_G} \left[1 - \frac{\sigma_P}{\sigma} \right] + \sum_{j=1}^J \frac{\dot{v}_{Gj}}{v_{Gj}} \frac{\sigma_{Gj}}{\sigma} \frac{Y_{Gj}}{Y} + \sum_{j=1}^J \frac{\dot{v}_{Pj}}{v_{Pj}} \frac{\sigma_{Pj}}{\sigma} \frac{Y_{Pj}}{Y}. \quad (\text{C.5})$$

The first term is the scale effect, equal to the change in aggregate output. The second term is the technique effect. As the SOE share increases, emissions rise if the private emissions intensity is less than the economy wide average emissions intensity. The last two terms are the composition effect. The composition effect varies by sector according to the relative emissions intensity of the industry and the industry share of output.

D Appendix: Tables and Figures

Parameter	symbol	Value	Source
Population Growth Rate	n	1.01	Demographic data.
Productivity Growth Rate	γ	1.02	Kehoe and Prescott (2002).
Depreciation Rate	δ	0.08	Bajona and Chu (2010).
TFP, Investment Production	A_I	2.40	Equation (4.3)
Elasticity Parameter	ρ	-1	Within RBC range.
Risk Aversion Parameter	χ	0	Given.
Discount Factor	β	0.96	One year time period.
Foreign/Domestic elasticity parameter	ζ	0.5	AGE literature.
Foreign Armington parameter	ζ_F	0.5	AGE literature.
Domestic tariff	τ_D	0.02	Tiwari, et. al. (2002)
World tariff	τ_F	0.05	Tiwari, et. al. (2002)
Initial Labor	L_0	4.30	CSY I/O tables.
Initial capital	K_0	21.68	CSY Industry tables.

Table 1: Scaler economic parameters. CSY is China Statistical Yearbook. For parameters where the source is an equation, it indicates the parameter is calibrated to satisfy the equation. Initial capital and capital are normalized so that initial output is 10.

Sym.	Source/Sector	Mining and quarrying	Textiles, sewing, leather, and fur products	Other manufacturing	Production and supply of electric power, steam, and hot water	Coking, gas, and petroleum refining	Chemical industry	Building materials and non-metal mineral products	Metal products	Machinery and equipment
α	Equation (B.3)	0.17	0.33	0.42	0.63	0.2	0.34	0.32	0.2	0.35
A_P	Equation (B.4)	6.36	5.64	5.95	1.24	21.59	7.83	6.82	11.35	6.42
A_G	Equation (B.4)	3.41	2.39	2.6	0.97	16.72	4.29	2.57	7.38	3.27
A_M	Equation (4.2)	1.79	1.54	1.53	1.49	1.78	1.77	1.22	1.65	1.77
μ	Equation (B.6)	0.68	0.78	0.78	0.79	0.68	0.68	0.9	0.73	0.68
D	Equation (4.11)	0.16	1.64	0.58	0.02	0.08	0.64	0.13	0.48	1.64
ν	Equation (B.5)	0	0.09	0.04	0	0.01	0.05	0.03	0	0.78
ϵ	Equation (B.7)	0.04	0.04	0.05	0.13	0.51	0.02	0.09	0.07	0.05
L_G/L	<i>CLSY</i>	0.88	0.37	0.33	0.84	0.82	0.45	0.49	0.62	0.46
s	Equation (B.8)	0.69	0.6	0.59	0.05	0.62	0.59	0.55	0.61	0.55
t	Equation (B.1)	0.04	0.07	0.04	0.06	0.05	0.05	0.05	0.03	0.05
G	I/O Tables, <i>CSY</i>	0	0	0	0	0	0	0	0	0

Table 2: Calibration of the sectoral parameters.

Parameters are: α : capital share, A_P and A_G : gross domestic output TFP, A_M : final goods productivity, μ : weight of sector's domestic good in the production of sector's final good, D : foreign demand parameter, ν : investment goods production share parameter, ϵ : weight consumers put on sectoral consumption relative to other consumption goods, L_G/L : SOE share of labor compensation, s : interest subsidy, t : production tax rate, g : government spending. Tax rates and productivity parameters are computed using value added plus intermediate inputs production. Parameters with monetary units are normalized so that initial output is 10. For parameters where the source is an equation, it indicates the parameter is calibrated to satisfy the given equation.

Sector	Mining and quarrying	Textiles, sewing, leather, and fur products	Other manufacturing	Production and supply of electric power, steam, and hot water	Coking, gas, and petroleum refining	Chemical industry	Building materials and non-metal mineral products	Metal products	Machinery and equipment
Mining and quarrying	0.13	0	0.02	0.29	0.68	0.06	0.15	0.13	0.01
Textiles, sewing, leather, and fur products	0.01	0.46	0.09	0.01	0	0.05	0.02	0.01	0.01
Other manufacturing	0.03	0.01	0.28	0.02	0.01	0.03	0.08	0.06	0.02
Production and supply of electric power, steam, and hot water	0.08	0.01	0.03	0.05	0.03	0.05	0.06	0.06	0.01
Coking, gas, and petroleum refining	0.04	0	0.01	0.08	0.06	0.03	0.04	0.03	0.01
Chemical industry	0.08	0.09	0.1	0.01	0.03	0.49	0.07	0.03	0.08
Building materials and non-metal mineral products	0.02	0	0.01	0.01	0.01	0.01	0.18	0.03	0.02
Metal products	0.07	0	0.06	0.01	0.01	0.02	0.07	0.45	0.16
Machinery and equipment	0.15	0.01	0.03	0.17	0.05	0.03	0.06	0.06	0.35

Table 3: Calibration a_{ji} . Column j row i represents the amount of i needed to produce one unit of j . Source: CSY I/O table.

For Tables 4-5, models are (1) OLS, (2) industry fixed effects, (3) industry fixed effects with time trend, and (4) industry fixed effects with year specific effects. T-statistics calculated using standard errors corrected for heteroskedasticity are below the coefficients, and an asterisk indicates significance at the 95% level.

Econometric Model	SO ₂				Soot			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
constant	-0.16 (-1.60)				-0.03 (-0.63)			
$\sigma_G - \sigma_P = \eta_1$	3.57* (3.22)	2.23* (9.30)	1.42* (2.73)	1.23* (2.41)	1.82* (2.86)	1.29* (7.09)	0.66 (1.84)	0.49 (1.43)
η_2	-2.05* (-1.99)	-1.22* (-3.90)	-1.00* (2.70)	-1.74* (-2.94)	-1.18* (-2.01)	-0.64* (-2.69)	-0.47 (-1.70)	-1.05* (-2.34)
$\eta_1 + \eta_2$	1.52* (3.99)	1.02* (3.50)	0.43 (1.16)	-0.50 (-0.87)	0.64* (3.95)	0.65* (2.72)	0.19 (0.70)	-0.56 (-1.32)
Implied σ_G	2.92	2.21	1.78	1.68	1.52	1.24	0.90	0.81
Implied σ_P	-0.65	-0.02	0.36	0.44	-0.30	-0.05	0.24	0.32
Time trend			-0.02 (-1.85)				-0.02* (-2.05)	
1995 Time Dummy				0.09 (0.51)				0.14 (1.01)
1996 Time Dummy				-0.04 (-0.24)				-0.00 (-0.01)
1999 Time Dummy				0.44 (1.76)				0.41 (1.80)
2000 Time Dummy				0.39 (1.66)				0.31 (1.58)
2001 Time Dummy				0.29 (1.36)				0.27 (1.56)
2002 Time Dummy				0.21 (1.06)				0.21 (1.32)
2003 Time Dummy				0.11 (0.58)				0.13 (0.87)
2005 Time Dummy				0.01 (0.04)				0.04 (0.33)
2006 Time Dummy				-0.05 (-0.29)				-0.01 (-0.04)
2007 Time Dummy				-0.11 (-0.60)				-0.05 (-0.33)
R^2	0.186	0.941	0.942	0.945	0.169	0.864	0.865	0.872
Adjusted R^2	0.207	0.944	0.945	0.945	0.187	0.857	0.859	0.859

Table 4: Regression coefficients and results for SO₂ and soot, 296 observations. Units for pollution intensity coefficients (σ and η) are tons per hundred thousand 1990 yuan.

Econometric Model	Industrial Dust				COD			
	(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
constant	0.27* (2.97)				0.45* (3.57)			
$\sigma_G - \sigma_P = \eta_1$	0.40 (1.66)	2.14* (3.73)	1.66* (2.95)	1.68* (3.05)	1.66 (1.66)	3.60* (2.83)	1.28 (1.04)	1.46 (1.27)
η_2	-0.45 (-1.67)	-0.29 (-1.82)	-0.16 (-0.95)	-0.60 (-1.76)	-1.23 (-1.97)	-1.08* (-2.49)	-0.45 (-1.10)	0.73 (1.07)
$\eta_1 + \eta_2$	-0.06 (-0.50)	1.85* (2.97)	1.50* (2.46)	1.08* (2.58)	-0.39* (-2.13)	2.52* (2.64)	0.83 (0.89)	2.19 (1.58)
Implied σ_G	1.18	2.11	1.85	1.86	1.01	2.48	1.25	1.34
Implied σ_P	0.79	-0.03	0.20	0.19	0.17	-1.12	-0.03	-0.12
Time trend			-0.01 (-0.91)				-0.07* (-2.51)	
1995 Time Dummy				-0.21 (-1.34)				0.12 (0.17)
1996 Time Dummy				-0.26 (-1.72)				-0.20 (-0.38)
1999 Time Dummy				0.30 (0.59)				-0.83 (-1.13)
2000 Time Dummy				0.12 (0.35)				-0.90 (-1.28)
2001 Time Dummy				-0.20 (-0.89)				-1.21 (-1.75)
2002 Time Dummy				-0.20 (-0.90)				-1.22 (-1.77)
2003 Time Dummy				-0.24 (-1.04)				-1.19 (-1.76)
2005 Time Dummy				-0.21 (-0.87)				-1.09 (-1.65)
2006 Time Dummy				-0.23 (-0.90)				-1.08 (-1.64)
2007 Time Dummy				-0.24 (-0.88)				-1.07 (-1.62)
R^2	0.013	0.780	0.780	0.790	0.029	0.666	0.672	0.681
Adjusted R^2	0.006	0.738	0.738	0.748	0.022	0.672	0.631	0.643

Table 5: Regression coefficients and results for industrial dust and COD, 296 observations. Units for pollution intensity coefficients (σ and η) are tons per hundred thousand 1990 yuan.

	Steady State (% above Baseline)				
Experiment	Y	SO ₂	Soot	Dust	TT
Decrease S by 5%	2.36	-2.35	-1.78	-11.62	-0.71
Decrease s by 2%	-0.01	-1.67	-1.48	-5.37	0.02
Decrease s 2%, S 5%	2.35	-3.86	-3.13	-16.47	-0.70
Decrease τ_F to 0	0.9	0.87	0.92	1.45	2.90

Table 6: Steady state results of numerical experiments. Percent change relative to the benchmark scenario. ‘TT’ is the change in terms of trade.

Scale Effect			
	Steady State as Percentage above Baseline		
Experiment	SO ₂	soot	Dust
Decrease S by 5%	2.36	2.36	2.36
Decrease s by 2%	-0.01	-0.01	-0.01
Decrease s 2%, S 5%	2.35	2.35	2.35
Decrease τ_F to 0	0.9	0.9	0.9
Technique Effect			
	Steady State as Percentage above Baseline		
Experiment	SO ₂	soot	Dust
Decrease S by 5%	-4.78	-4.19	-13.36
Decrease s by 2%	-1.86	-1.63	-5.2
Decrease s 2%, S 5%	-6.43	-5.64	-17.99
Decrease τ_F to 0	-0.06	-0.05	-0.16
Composition Effect			
	Steady State as Percentage above Baseline		
Experiment	SO ₂	soot	Dust
Decrease S by 5%	0.17	0.13	-0.33
Decrease s by 2%	0.2	0.16	-0.16
Decrease s 2%, S 5%	0.35	0.27	-0.46
Decrease τ_F to 0	0.03	0.07	0.71

Table 7: Scale, technique, and composition effects. Percent change relative to the benchmark scenario. Effects do not sum exactly to the total effect as derivatives since the change in subsidies is not marginal (for example, $\frac{\dot{Y}}{Y}$ in equation C.5 does not exactly equal $\frac{Y_s - Y_B}{Y_B}$, where Y_s is production after the policy change and Y_B is benchmark).

Steady State as a Percent of Baseline			
$\hat{\eta}_1$ Reduced by one standard deviation			
Experiment	SO ₂	Soot	Dust
Decrease S by 5%	-1.02	0.18	-13.32
Decrease s by 2%	-1.12	-0.68	-5.95
Decrease s 2%, S 5%	-2.04	-0.43	-18.7
Decrease τ_F to 0	0.87	0.93	1.9
$\hat{\eta}_1$ From regression with year specific effects			
Experiment	SO ₂	Soot	Dust
Decrease S by 5%	-2.15	-1.53	-7.58
Decrease s by 2%	-1.54	-1.28	-3.8
Decrease s 2%, S 5%	-3.55	-2.68	-11.02
Decrease τ_F to 0	0.79	0.78	1.22
A_P/A_G Reduced by half			
Experiment	SO ₂	Soot	Dust
Decrease S by 5%	-3.82	-3.31	-10.65
Decrease s by 2%	-2.21	-2.05	-5.01
Decrease s 2%, S 5%	-5.82	-5.17	-15.18
Decrease τ_F to 0	0.89	0.92	1.32
Reduce production taxes, keep lump sum taxes constant			
Experiment	SO ₂	Soot	Dust
Decrease S by 5%	-1.36	-0.76	-10.66
Decrease s by 2%	-1.23	-1.03	-4.91
Decrease s 2%, S 5%	-2.5	-1.71	-15.21
Decrease τ_F to 0	0.67	0.7	1.22

Table 8: Sensitivity analysis: Results of numerical experiments. Percent change relative to the benchmark scenario.

Industry	SO ₂	Soot	Dust
Mining and quarrying	0.46	0.21	0.43
Textiles, sewing, leather, and fur products	0.58	0.27	0.63
Other manufacturing	0.56	0.27	0.57
Production and Supply of electric power, steam, and hot water	0.44	0.21	0.6
Coking, gas, and petroleum refining	0.17	0.08	0.19
Chemical industry	0.32	0.15	0.34
Building materials and non-metal mineral products	0.4	0.19	0.47
Metal products	0.24	0.11	0.24
Machinery and equipment	0.46	0.22	0.52

Table 9: Difference in emission intensities, $\sigma_{Gj} - \sigma_{Pj}$, in tons per 10K 1990 yuan of aggregate output.

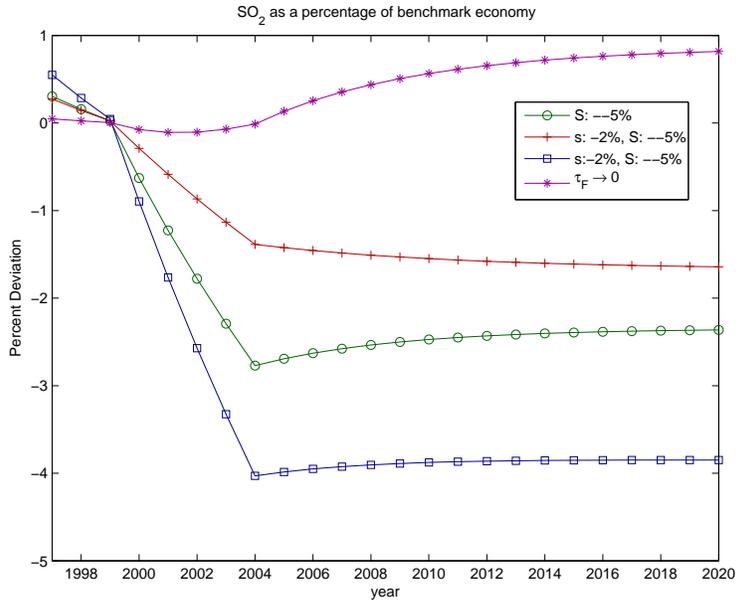


Figure 1: Sulfur Dioxide Emissions. Percent change relative to the benchmark scenario. Changes in tariffs and subsidies are phased in over years 2000-2004.

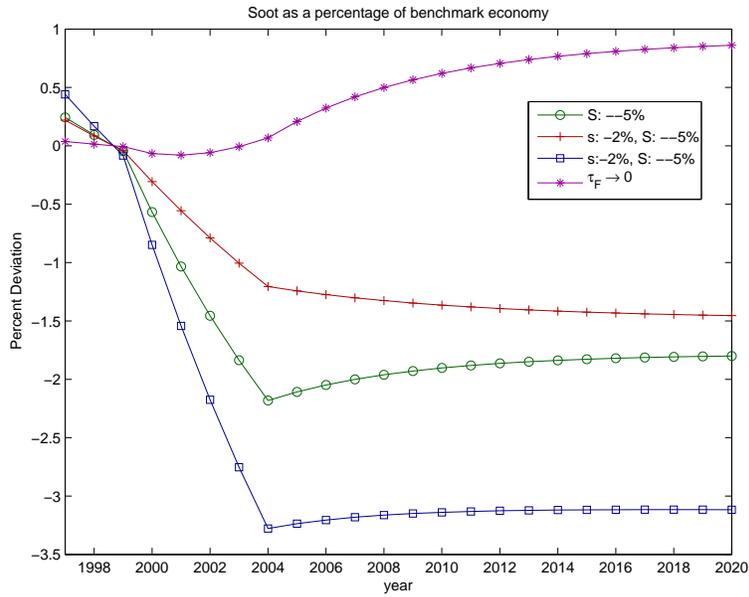


Figure 2: Soot Emissions. Percent change relative to the benchmark scenario. Changes in tariffs and subsidies are phased in over years 2000-2004.

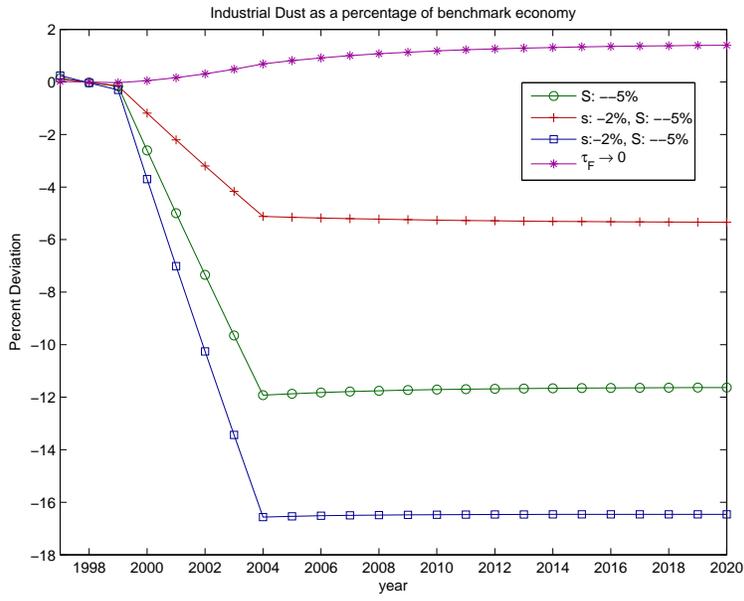


Figure 3: Industrial dust emissions. Percent change relative to the benchmark scenario. Changes in tariffs and subsidies are phased in over years 2000-2004.

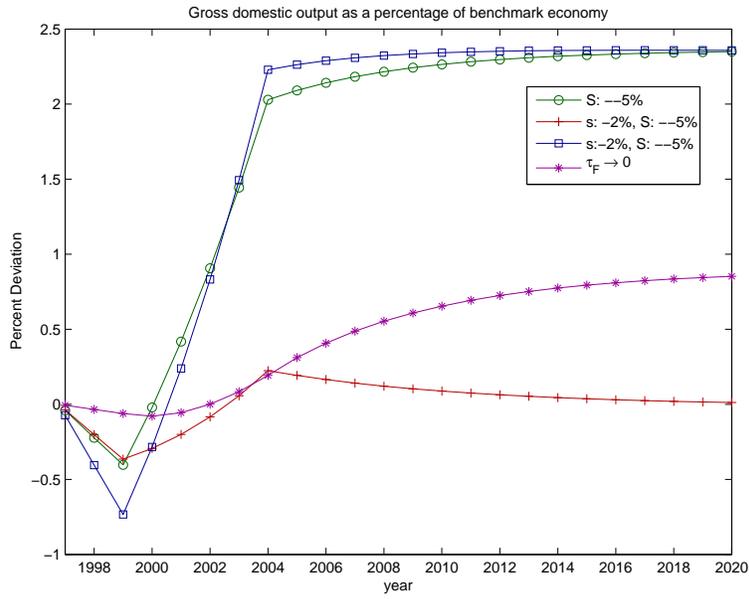


Figure 4: Aggregate Output. Percent change relative to the benchmark scenario. Changes in tariffs and subsidies are phased in over years 2000-2004.

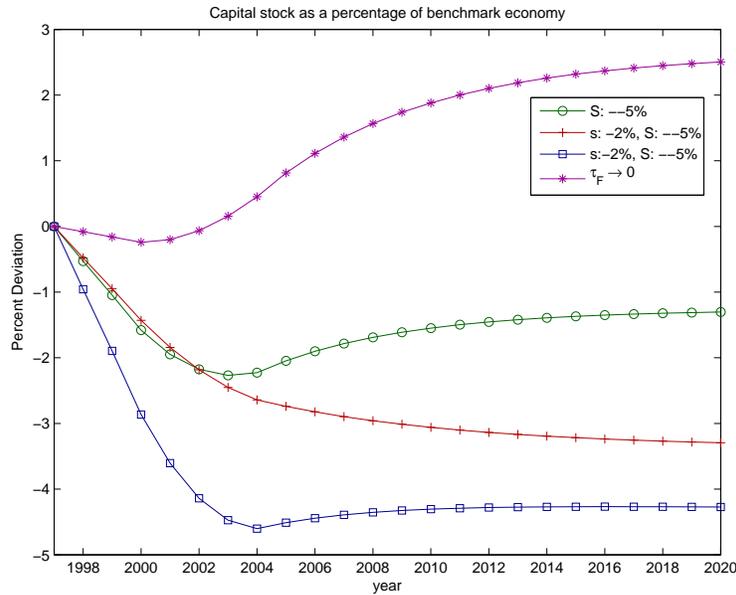


Figure 5: Aggregate capital stock. Percent change relative to the benchmark scenario. Changes in tariffs and subsidies are phased in over years 2000-2004.

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