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Accounting for loss of variety and factor reallocations in the welfare cost of regulations

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ABSTRACT

This paper develops a multi-sector general equilibrium model with heterogeneous firms to account for both the direct cost of regulations on regulated firms as well as the indirect cost associated with loss of variety and factor reallocations. The model derives an analytical marginal abatement cost function, dividing the cost according to these direct and indirect effects, and explores the implications for optimal environmental policy. The model is numerically simulated using parameters for the U.S. manufacturing sector for criteria air pollutants, demonstrating that the direct cost of regulations understates the true cost. Moreover, because marginal abatement costs vary across industries, reallocating pollution across industries to achieve cost-effectiveness can generate modest cost savings.

1. Introduction

The direct burden of environmental regulations on regulated firms is often an imperfect measure of the social burden for a variety of reasons. Examples include interactions of regulations with the exercise of market power (Buchanan, 1969; Ryan, 2012; Fowlie et al., 2016) and pre-existing tax distortions (Bovenberg and de Mooij, 1994; Parry, 1995; Goulder et al., 1999; Fullerton and Metcalf, 2001; Goulder et al., 2016), and leakage due to incomplete regulation (Bernard et al., 2007; Holland, 2012). Despite empirical evidence that regulations cause some firms to cease operations and exit the market (Greenstone et al., 2012), studies generally abstract from firm entry-exit decisions, as well as changes in product variety. This paper adds to the literature by developing a model to account for the welfare cost associated with loss of variety and factor reallocations induced by environmental regulations, and explores the implications for optimal environmental policy.

The model can be explained intuitively as follows. Consider an industry where firms produce differentiated goods, and differences in productivity generate differences in profits, where the least productive firm earns zero profits. In effect, environmental regulations, which induce or require firms to divert productive resources to pollution mitigation, increase cost. Firms that, prior to the change in regulations, were only "marginally" profitable would be rendered unprofitable after

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the change and would consequently exit the market.

In addition to the direct compliance cost, regulations therefore generate two indirect effects. First, because ex-post active firms are on average more productive than ex-ante active firms, productive resources are reallocated from less to more productive firms, resulting in higher average productivity and in turn lower prices. Second, because firms produce differentiated goods, firms exiting the market represent a loss of variety to consumers, which reduces welfare. Because the two are confounding in nature, the direct burden of regulations might understate or overstate the true, or at least more comprehensive, welfare cost.

The model also sheds light on optimal environmental policy. That is, when environmental regulations induce firm exit, imposing a uniform cost of emissions across industries, or allowing the trade of emissions permits between industries on a one-to-one basis, does not minimize the welfare cost of achieving a given level of emissions reductions. For example, the model demonstrates that industries with more differentiated products should face relatively lower cost of emissions compared to industries with less differentiated products, even when industries emit pollution with identical damages. Moreover, the second-best optimal level of pollution should account for the indirect, as well as the direct, effects of regulations.

This paper contributes to two areas of research. First, this paper contributes to the literature investigating the economic cost of environmental regulations, particularly in the context of the manufacturing sector (Greenstone, 2002; Becker and Henderson, 2000; Becker, 2005; Greenstone et al., 2012). Second, this paper contributes to the handful of studies analyzing the role of firm heterogeneity in environmental policy (Tombe and Winter, 2015; Li and Sun, 2015; Konishi and Tarui, 2015; Anouliès, 2017).

One of the most significant, and extensively studied, set of environmental regulations is the U.S. Clean Air Act and the subsequent Clean Air Act Amendments (CAAAs), and their impact on the manufacturing sector.[1] Among studies investigating the economic cost of the CAAAs, most rely on county-level variation in regulatory stringency according to national ambient air quality status (NAAQS) (attainment or non-attainment)[2] and focus on either extensive-margin effects (e.g., plant death and births) or intensive-margin effects (e.g., output and productivity), or the direct cost of mandated pollution abatement equipment.[3] For example, empirical studies document that polluting industries tend to migrate from attainment to non-attainment counties (Henderson, 1996), and non-attainment is associated with fewer firm births (Becker and Henderson, 2000; List et al., 2003). Non-attainment is also associated with greater expenditures on pollution abatement equipment among heavy emitters (Becker, 2005), although data on pollution abatement expenditures are notably incomplete. Finally, non-attainment is also associated with lost output (Greenstone, 2002), and reduced total-factor productivity among establishments in polluting industries (Greenstone et al., 2012).

What do these studies imply in terms of the welfare cost of regulations? Because pollution abatement expenditures do not fully reflect all of the costs associated with regulations[4] and "lost" output due to regulations might be offset (at least in part) by increases in output elsewhere (e.g., less polluting industries), a more reflective measure of the (intensive-margin) economic cost of regulations is the impact on firm productivity (Greenstone et al., 2012).[5] Greenstone et al. (2012) estimate that non-attainment is associated with a 2.6 percent decline in total-factor productivity (TFP) among surviving plants in polluting industries. Holding inputs constant, this corresponds to an economic cost of lost output around $11 billion in 2010 dollars.

Reducing productivity is not the only effect of regulations, however, as they also cause some firms to exit the market (Greenstone et al., 2012), particularly the least productive firms.[6] Greenstone et al. (2012) argue that because the estimated TFP effects are conditional on survival, the actual TFP effects are larger due to survivorship (selection) bias. Correcting for survivorship bias implies that non-attainment is associated with a (larger) 3.3 percent reduction in TFP, and applying the same procedure to calculate the economic cost implies that the corresponding lost output was around $14.3 billion.

While correcting for survivorship bias is appropriate to estimate the TFP effect of regulations among surviving and non-surviving firms, the welfare costs associated with reductions in productivity among surviving and non-surviving firms are not generally equal. Put more simply, once productivity is reduced to a point such that remaining in the market is unprofitable, further reductions in productivity are immaterial from a welfare point of view, at least in the long-run as the firm's factors of production would be reallocated. Moreover, when firms produce differentiated goods, firm exit would also be associated with loss of variety, which would generate an additional welfare cost. In sum, when regulations induce firm exit, the TFP effect is not a sufficient statistic for welfare, and assessing the welfare cost of regulations requires a framework that incorporates costs associated with loss of product variety and factor reallocations. This study fills this gap.

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[1] See Becker and Henderson (2000) or Greenstone (2002) for details regarding the background of the CAAAs.

[2] Non-attainment is associated with more stringent regulations because if a county is in non-attainment status, the state must implement policies to bring down air pollution to comply with federal standards.

[3] Other studies examine the cost of regulations in terms of disemployment effects and the cost of foregone earnings (Greenstone, 2002; Walker, 2013), which is beyond the scope of this paper.

[4] For example, pollution abatement expenditures do not include costs associated with changing the production process (Gray and Shadbegian, 1995).

[5] Greenstone et al. (2012) argue that their study, which estimates the effect of regulations on productivity, is the first to estimate the "economic costs" for the manufacturing sector. This paper refers to the direct effect of regulations as "cost" rather than "productivity" effects for clarity as firm productivity will vary for technological reasons.

[6] Several empirical studies document a negative correlation between productivity and plant death (see Bartelsman and Doms, 2000 for a review of the literature).

This paper also contributes to the literature examining the role of firm heterogeneity in environmental policy. Konishi and Tarui (2015) and Anouliès (2017) compare the welfare cost of an emissions trading program under various allocation rules, while Li and Sun (2015) compare the welfare cost of emissions taxes and standards.[7] Similarly, Tombe and Winter (2015) compare the aggregate productivity effects of emissions taxes and standards, and quantify the effects for energy taxes and energy-efficiency standards.[8] The primary insight of these studies is that policies that achieve similar levels of pollution abatement have dissimilar effects on firm entry and exit decisions, which in turn bears on the cost-effectiveness of policies. Moreover, in the context of firm heterogeneity, the conventional wisdom that emissions taxes (or auctioned permits) are more cost-effective than alternative instruments does not necessarily hold. While these studies shed light on the relative cost-effectiveness of discrete policy instruments, the broader issue of how environmental policy should respond to firm heterogeneity and endogenous entry-exit decisions remains open.

More generally, this paper fits into the vast literature building on the Dixit and Stiglitz (1977) model of monopolistic competition, and the more recent international-trade literature incorporating heterogeneous firms (Melitz, 2003). While exposure to foreign trade is conceptually distinct from environmental regulations, the indirect effects of regulations are akin to the trade-induced reallocation and variety effects described in the international trade literature (Melitz, 2003). In contrast to the welfare effects of regulations analyzed in the present paper, an insight of the literature is that the welfare gain associated with factor reallocations (increased average productivity) dominates the welfare loss associated with reduced product variety, as the latter effect is offset by increased imports of foreign varieties. While this paper focuses on environmental regulations, the conceptual analysis has insights with respect to the welfare effects of regulations more generally (such as occupational safety laws) as well as the optimal pricing of publicly-supplied productive inputs (such as natural resource use) in the context of monopolist competition and firm heterogeneity.[9]

This paper develops a tractable general equilibrium model to account for the direct cost effect of regulations and the indirect effects arising from endogenous firm exit. The model incorporates pollution emissions and endogenous pollution abatement in a multi-sector Dixit and Stiglitz (1977) model of monopolistic competition. Firms vary according to productivity and produce a unique variety using an increasing returns to scale technology. Moreover, firms respond to environmental regulations, modelled as a per-unit cost of pollution, by allocating productive resources to pollution abatement, thereby increasing cost. Industries are characterized by distinct elasticities of substitution across varieties, productivity distributions, and pollution abatement technologies (or pollution intensities).

The model divides the effect of regulations into three analytically distinct effects: (i) cost, (ii) average-productivity, and (iii) variety effects. The cost effect refers to the direct cost associated with compliance of regulations; the average-productivity effect refers to the increase in average productivity associated with factor reallocations to ex-post more productive firms; and the variety effect refers to the loss of variety associated with ex-post fewer number of firms.[10] The model demonstrates that, while the indirect effects of regulations (ii) and (iii) are confounding in nature, the variety effect exceeds the average-productivity effect, implying that the true welfare cost of regulations is greater than the direct cost. While the direct cost is not a sufficient statistic for the welfare cost of regulations, the model demonstrates that the true welfare cost is proportional to the direct cost, where the proportionality factor is a fixed constant that depends on (i) the elasticity of substitution across varieties and (ii) the degree of dispersion in the distribution of firm productivities (or firm size). Finally, the model results in an analytical solution for the marginal abatement cost of pollution reductions by industry, and divides the cost according to the costs arising from the three effects described above.

The model is numerically simulated for the U.S. manufacturing sector for criteria air pollutants using parameters recently estimated by Shapiro and Walker (2015).[11] The numerical model results indicate that marginal abatement costs range from \$145 to \$193 across industries per ton of air pollution. Variation in costs is primarily the consequence of variation in the indirect cost of regulations, and the true welfare cost is between 3% and 20% greater than the direct cost of regulations. The aggregate marginal abatement cost depends on the total amount of abatement undertaken and the allocation of pollution across industries. Holding the allocation of pollution constant, aggregate marginal abatement cost is \$159 per ton of air pollution, and increases to \$188 after reducing pollution by 15%, and increases further to \$232 after reducing pollution by 30% (and so on).

What are the policy implications? In calculating the welfare cost of regulations, the model indicates that the true welfare cost of regulations is 9% greater than the direct cost, irrespective of the amount of pollution abatement undertaken. The model also demonstrates that, because marginal abatement costs exhibit variation across industries, reallocating pollution across industries to satisfy the equimarginal principle would result in a welfare savings of around \$72 million dollars. Finally, the second-best optimal pollution level is 9% greater as a consequence of accounting for the indirect effect of regulations.

[7] Li and Shi (2011) also investigate welfare impacts of emissions taxes and standards, but do not account for firm exit and entry.

[8] Tombe and Winter (2015) provide a compelling argument that the analysis is isomorphic to pollution emissions, which is perhaps accurate in the case of carbon dioxide emissions, but less accurate in the case of other pollutants.

[9] The latter is a consequence of the result that pollution can be treated as if it were a productive input in production. Schröder and Sørensen (2010). investigate the welfare effects of unit and ad valorem taxes but not input taxes–the former is more relevant to revenue extraction whereas the latter is more relevant to correcting externalities.

[10] "Factor reallocations" refers to the change in the allocation of inputs across firms, but this paper uses the term average-productivity effect because it is more directly related to welfare.

[11] Pollution is tons of emissions of criteria air pollutants: CO, NO_x, PM_{10}, $PM_{2.5}$, SO_2, and VOC.

2. Model

This section presents a general equilibrium model with heterogeneous firms based on the Dixit and Stiglitz (1977) model of monopolistic competition.[12] While I consider a closed economy, the general setup is similar to that of Melitz (2003). The model accounts for both firm-level impacts of environmental regulations, as well as general equilibrium impacts associated with endogenous entry-exit decisions.

2.1. Consumers

Welfare is defined as the following function:

$$W = U\psi(Z) \tag{1}$$

where U is consumption utility and $\psi(Z)$ is multiplicative pollution damages (externality) associated with aggregate pollution Z. Because the primary focus of the analysis is the welfare cost of regulations, multiplicative damages are expedient to distinguish between the cost of regulations and pollution damages. Consumption utility exhibits constant elasticity of substitution (CES) across varieties within a sector, and Cobb-Douglas preferences between sectors. That is,

$$U = \prod_{j \in J} \left(\left[\int_{\omega \in \Omega_j} q(\omega)^{\frac{\sigma_j - 1}{\sigma_j}} d\omega \right]^{\frac{\sigma_j}{\sigma_j - 1}} \right)^{\beta_j} \tag{2}$$

where $q(\omega)$ is demand for variety ω, and Ω_j is the mass of available varieties in sector $j \in J$. The parameter σ_j is the elasticity of substitution across varieties within sector $j \in J$, where any two goods are assumed to be substitutes (that is, $\sigma_j > 1$). Greater substitutability across varieties implies that products are less differentiated (or demand is more elastic). Cobb-Douglas preferences across sectors imply constant expenditure shares across sectors, where β_j is the share of expenditures devoted to sector $j \in J$ and $\sum_{j \in J} \beta_j = 1$.

2.2. Producers

There is a continuum of firms producing different varieties and with different productivity levels $\phi > 0$, where higher ϕ represents higher productivity. As demonstrated by Dixit and Stiglitz (1977), firms produce a single variety, and for notational convenience, firms are indexed according to productivity. Production is linear in a composite input "labor," which includes human capital, physical capital, fuel, energy, materials, and so on. All firms in a given sector share a common fixed production cost of $f_j > 0$ units of labor. Firms generate a joint bad (pollution) in production, and allocate an endogenous fraction $0 < \theta < 1$ of labor to pollution abatement. The total amount of labor l required to produce q units of a variety therefore satisfies:

$$(1 - \theta)l = \left(\frac{q}{\phi} + f_j \right) \tag{3}$$

Following Copeland and Taylor (2003), I assume that pollution is given by:[13]

$$z = (1 - \theta)^{1/\alpha_j} l \tag{4}$$

As conventional, I assume that $0 < \alpha_j < 1$, which implies that allocating resources to abatement reduces pollution, but marginal reductions in pollution are decreasing as the amount of abatement resources increase. Expressions (3) and (4) imply that production and abatement choices can be represented by the following production-pollution technology:

$$z^{\alpha_j} l^{1-\alpha_j} = \left(\frac{q}{\phi} + f_j \right) \tag{5}$$

That is, the production and abatement technologies can be represented as a constant returns to scale technology with inputs labor and pollution.

[12] The Dixit and Stiglitz (1977) model has been widely adopted in various economic fields, such as international trade (e.g., Melitz, 2003). Because the theoretical predictions of Melitz (2003) are consistent with empirical regularities in manufacturing sectors, and because many pollution-intensive sectors have become differentiated-good industries (such as chemicals and metals industries) (Konishi and Tarui, 2015), several papers have adapted the Melitz (2003) framework to account for pollution emissions (Kreickemeier and Richter, 2013; Li and Sun, 2015; Konishi and Tarui, 2015; Shapiro and Walker, 2015; Andersen, 2016; Anouliès, 2017, among others).

[13] The Copeland and Taylor (2003) production-pollution technology is a standard approach to modelling pollution in models with firm heterogeneity and monopolistic competition. Examples include Martin (2011), Konishi and Tarui (2015), Anouliès (2017),Shapiro and Walker (2015), Li and Sun (2015), and Tombe and Winter (2015).

I assume that the labor market is perfectly competitive with an equilibrium wage rate w. The stringency of regulations are modelled as a per-unit cost of pollution $\tau_j > 0$, where higher τ_j represents more stringent environmental policy. Because the production-pollution technology exhibits constant returns to scale, cost minimization yields the following cost function:

$$C_j(q;\, w,\, \tau_j) = \left[\frac{q}{\phi} + f_j\right] c_j(w,\, \tau_j) \tag{6}$$

where $c_j(w, \tau_j) f_j$ is the fixed production cost, and $c_j(w, \tau_j)/\phi$ is the constant marginal cost of a firm with productivity ϕ. Because the production-pollution technology is Cobb-Douglas, it is straightforward that $c_j(w, \tau_j) = A_j \tau^{\alpha_j} w^{1-\alpha_j}$, where $A_j = \alpha_j^{-\alpha_j}(1-\alpha_j)^{-(1-\alpha_j)} > 0$ is a fixed parameter. Without loss of generality, I choose labor as the numeraire so that $w = 1$. Also, I suppress the argument in $c_j(1, \tau_j) \equiv c_j$ whenever convenient. As conventional in monopolist-competition models (Dixit and Stiglitz, 1977), firms set prices equal to a constant markup over marginal cost $p_j(\phi) = c_j/(\rho_j \phi)$, where $\rho_j \equiv (\sigma_j - 1)/\sigma_j$.[14]

The Cobb-Douglas production-pollution technology has several properties that are convenient from a modelling point of view. For example, the parameter α_j is the elasticity of cost with respect to τ_j and the exogenous share of pollution expenditures in total cost. The parameter α_j can thus be interpreted as the pollution intensity of the industry, where higher values of α_j correspond to greater pollution intensity.

Because cost shares are identical across firms, it follows that emissions-to-labor ratios are constant within industries, but more productive firms generate less emissions per unit of output due to having lower input requirements.[15] That productivity is inversely related to emissions intensity is consistent with both industry-level (Cole et al., 2005, 2008) and plant-level (Martin, 2011; Shapiro and Walker, 2015) empirical studies. However, the relationship might be explained, at least in part, by more productive firms allocating a greater share of resources to pollution abatement. For example, certain abatement technologies might entail high fixed costs that can only be rationalized for more productive firms with sufficient scales of production. Section 2.7 extends the model to allow firms to invest in a discrete abatement-technology upgrade, and demonstrates that the results are not affected under certain conditions.

2.3. Firm entry and exit

In every sector, there is a pool of potential entrants, which are identical prior to entry. Entry requires paying a fixed entry cost, which includes investment in research and development, obtaining business licenses, and so on. The fixed entry cost is measured in units of labor, and is represented by the parameter $f_j^e > 0$.[16] Upon paying the fixed entry cost, firms draw a random productivity parameter from the common distribution $g_j(\phi)$, which has a positive support over $(0, \infty)$ and cumulative distribution $G_j(\phi)$. Firm profits $\pi_j(\phi)$ are an increasing function of the productivity draw, and firms drawing a productivity parameter conferring negative profits $\pi_j(\phi) < 0$ immediately exit the market. The cutoff productivity level ϕ_j^* is defined according to the following zero cutoff profit (ZCP) condition:

$$\pi_j(\phi_j^*) = 0 \tag{ZCP}$$

Because profits are increasing in productivity, firms with productivity draws $\phi < \phi_j^*$ immediately exit the market.

For tractability, I assume that firm productivities are Pareto distributed, with the lower bound normalized to one, implying that $G_j(\phi) = 1 - \phi^{-k_j}$ and $g_j(\phi) = k_j \phi^{-(k_j+1)}$.[17] The Pareto density function is strictly decreasing, and the parameter k_j is the "tail index" where higher values correspond to fatter tails (that is, greater industry dispersion). As conventional, I assume that $k_j > \sigma_j - 1$. With the ex-ante productivity distribution being Pareto, the ex-post productivity distribution of incumbent firms is Pareto distributed with positive support over (ϕ_j^*, ∞). That is,

$$\mu_j(\phi) = \begin{cases} \dfrac{k_j}{\phi}\left(\dfrac{\phi_j^*}{\phi}\right)^{k_j} & \text{if} \phi \geq \phi_j^* \\ 0 & \text{if} \phi < \phi_j^* \end{cases} \tag{7}$$

where $\mu_j(\phi)$ is the distribution of productivities conditional on successful entry.

Potential entrants enter the market if ex-ante expected profits exceed the fixed cost of entry. In a stationary equilibrium, an incumbent firm with productivity $\phi \geq \phi_j^*$ earns $\pi_j(\phi) \geq 0$ every period, and exits the market with probability δ_j in each

[14] Because markups are constant, the model precludes endogenous markups from changes in market power, which simplifies the analysis greatly and ensures that the model retains tractability. Moreover, other studies have grappled with the issue of the role of market power in regulations (Ryan, 2012; Fowlie et al., 2016).

[15] Consistent with this assumption, Bloom et al. (2010) argue that the link between greater productivity (due to management practices) and lower emissions intensity (greenhouse gas pollution) is due to lower energy intensity in production.

[16] I assume that entry does not generate pollution and hence is independent of τ.

[17] Eaton et al. (2011), among others, document that firm size approximately follows this distribution, and this assumption is prevalent in the literature.

period. The corresponding value of entry is thus $\sum_{t=0}^{\infty}(1-\delta_j)^t \pi_j(\phi) = \pi_j(\phi)/\delta_j$, and the ex-ante expected value of entry is therefore equal to $(\bar{\pi}_j/\delta_j)(\phi_j^*)^{-k_j}$, where $\bar{\pi}_j$ is expected profits conditional on entry. Because entry is unrestricted, the ex-ante value of entry will equal the fixed entry cost in equilibrium. That is,

$$\bar{\pi}_j = \delta_j(\phi_j^*)^{k_j} f_j^e \tag{FE}$$

where expression (FE) represents the free entry condition.

The (ZCP) and (FE) conditions jointly govern entry and exit decisions in the economy. In particular, the two equations solve for the equilibrium average profit level $\bar{\pi}_j$ and cutoff productivity ϕ_j^*.

Result 1. An increase in the stringency of regulations increases the productivity threshold, thereby increasing average productivity. That is,

$$\tilde{\phi}_j = \left(\frac{k_j}{k_j - \sigma_j + 1}\right)^{\frac{1}{\sigma_j - 1}} \left(\phi_j^*\right), \quad \text{where} \quad \frac{d\tilde{\phi}_j/\tilde{\phi}_j}{d\tau_j/\tau_j} = \left(\frac{\alpha_j}{k_j}\right) > 0 \tag{8}$$

Proof. See Appendix C. □

The intuition for Result 1 is straightforward. An increase in the stringency of regulations increases cost, thereby increasing the productivity threshold such that firms earn zero profits. Average productivity is higher because the least productive firms are rendered unprofitable and therefore exit the market. This effect is larger among industries with less productivity dispersion because a greater mass of firms are marginally profitable. Moreover, this effect is larger among more pollution-intensive industries because unit cost increases by a greater extent among these industries.

2.4. Aggregation

I assume that the economy is endowed with a fixed supply of labor L that is employed in production and investment in entry across all sectors. For sectors $j \in J$, let the equilibrium labor employed be represented as L_j, the equilibrium pollution emissions be represented as Z_j, and the equilibrium mass of firms (or equivalently, the mass of varieties) be represented as M_j. Solving for firm pollution expenditures and integrating over all firms in the sector implies that (see Appendix):

$$Z_j = \frac{\alpha_j \eta_j \beta_j R}{\tau_j} \tag{9}$$

where R is economy-level aggregate expenditures and $\eta_j \equiv 1 - (\sigma_j - 1)/(k_j \sigma_j) \in (0, 1)$. Aggregate expenditures must equal the sum of aggregate payments to labor and pollution, which implies:

$$R = \frac{L}{\sum_{j \in J} \beta_j (1 - \alpha_j \eta_j)} \tag{10}$$

Because expenditure shares are constant, it follows that industry-level expenditures are given by $R_j = \beta_j R$. Expression (10) demonstrates that expenditures (or income) are independent of the stringency of regulations. Moreover, industry-level expenditures must equal the sum industry-level payments to labor and pollution, implying that the allocation of labor across sectors is the following:

$$\frac{L_j}{L} = \frac{(1 - \alpha_j \eta_j)\beta_j}{\sum_{j \in J} \beta_j (1 - \alpha_j \eta_j)} \tag{11}$$

Expression (11) demonstrates that regulations do not generate inter-industry reallocations as labor shares are independent of the stringency of regulations. Constant labor shares are a consequence of constant industry expenditure shares (Cobb-Douglas upper-tier preferences) and unit elasticity of pollution (Cobb-Douglas production-pollution technology).[18]

Result 2. An increase in the stringency of regulations decreases the mass of varieties. That is,

$$M_j = \left(\frac{k_j - \sigma_j + 1}{k_j}\right)\left(\frac{\beta_j R}{\sigma_j f_j c_j}\right), \quad \text{where} \quad \frac{dM_j/M_j}{d\tau_j/\tau_j} = -\alpha_j < 0 \tag{12}$$

Proof. See Appendix C. □

[18] Moreover, industry-level labor used in entry, fixed production, and variable production, are independent of the stringency of regulations (see Appendix).

Result 2 demonstrates that the percentage reduction in product varieties is equal to the percentage increase in unit cost. Consequently, more pollution intensive industries will experience a greater reduction in product varieties because unit costs increase by a greater extent among these industries.

2.5. Welfare cost of regulations

The welfare cost of regulations refers to the welfare loss (or gain) associated with an increase in the stringency of regulations. To shed light on this cost, consider the following decomposition of consumption utility (Melitz, 2003):

$$U = \prod_{j \in J} \left[R_j M_j^{\frac{1}{\sigma_j - 1}} \left(\frac{\tilde{\phi}_j \rho_j}{c_j} \right) \right]^{\beta_j} \tag{13}$$

Result 3. Decomposition of Welfare Costs:The effect of regulations potentially consists of three distinct effects: (i) cost, (ii) average-productivity, and (iii) variety effects.

$$\frac{dW/W}{d\tau_j/\tau_j} = \beta_j \left[-\frac{dc_j/c_j}{d\tau_j/\tau_j} + \frac{d\tilde{\phi}_j/\tilde{\phi}_j}{d\tau_j/\tau_j} + \left(\frac{1}{\sigma_j - 1} \right) \frac{dM_j/M_j}{d\tau_j/\tau_j} \right] \tag{14}$$

In particular, an increase in the stringency of regulations decreases welfare through cost effects, increases welfare through average-productivity effects, and decreases welfare through variety effects.

$$\frac{dW/W}{d\tau_j/\tau_j} = -\alpha_j \beta_j \Gamma_j \tag{15}$$

where

$$\Gamma_j(\sigma_j, k_j) = \left(1 - \frac{1}{k_j} + \frac{1}{\sigma_j - 1} \right) \tag{16}$$

Proof. Follows from (13), and Results 1 and 2. □

The parameter Γ_j divides the welfare cost of regulations according to the three effects highlighted by Result 3, where the first term is the cost effect, the second term is the average-productivity effect, and the third term is the variety effect. As expected, the average-productivity effect is decreasing in industry dispersion, while the variety effect is decreasing in the elasticity of substitution. The sum of the second and third terms represents the constant ratio of the indirect effect (average-productivity and variety) to the direct effect of regulations, while the parameter Γ_j represents the constant ratio of the true welfare cost to the direct cost of regulations.

Corollary 3.1. *The direct cost of regulations understates the true welfare cost. That is, the ratio of the true welfare cost to the direct cost* $\Gamma_j > 1$ *whenever* $k_j > \sigma_j - 1$.

Corollary 3.1 also demonstrates that the net effect of an increase in the stringency of environmental regulations (holding pollution constant) is unambiguously negative. While the direct cost of regulations is not a sufficient welfare statistic, accounting for average-productivity and variety effects turns out to be quite straightforward. That is, because Γ_j represents the ratio of the true welfare cost to the direct cost of regulations, multiplying the (weighted) increase in cost by Γ_j translates the direct cost of regulations into the true welfare cost. That is, Γ_j and in turn σ_j and k_j, are sufficient statistics for calculating the welfare cost of regulations.

More relevant to policy is the welfare cost of pollution reductions in terms of dollars, or the marginal abatement cost. That is (see Appendix),

$$MC_j^A = -\frac{1}{\lambda} \frac{dW/d\tau_j}{dZ_j/d\tau_j} = \frac{\alpha_j \beta_j \Gamma_j R}{Z_j \left(1 + \sum_{j \in J} \frac{\beta_j}{\sigma_j - 1} \right)} \tag{17}$$

where $\lambda = dW/dR$ is the marginal utility of income.[19]

The second implication is that a uniform emissions tax will not, in general, satisfy the equimarginal principle (that is, $\tau_j = \tau_i \Rightarrow MC_j^A \neq MC_i^A$). A necessary requirement for a cost-minimizing policy is therefore that industries face differential pollution tax rates, or more specifically,

[19] The marginal abatement cost is identical under linear pollution damages. The details are provided in the Appendix C (see the proof of expression (17)).

$$MC_j^A = MC_i^A \Rightarrow \frac{\tau_j}{\tau_i} = \frac{\Gamma_i/\Gamma_j}{\eta_j/\eta_i} \tag{18}$$

That is, for a given level of aggregate pollution emissions $Z = \sum_{j\in J} Z_j$, cost-effectiveness implies that the share of pollution generated by industry j should satisfy the following condition:

$$\frac{Z_j}{\sum_{j\in J} Z_j} = \frac{\alpha_j\beta_j\Gamma_j}{\sum_{j\in J}\alpha_j\beta_j\Gamma_j} \tag{19}$$

2.5.1. *Aggregate welfare cost of regulations*

In general, the welfare cost of regulations depends on the initial level of pollution Z^0, the amount of pollution reductions $Z^0 - Z$, and the allocation of pollution reductions. For notation, let ξ_j^0 represent the initial share of pollution emissions generated by industry j and ξ_j represent the share of pollution emissions after pollution is reduced to Z.

The welfare cost of reducing pollution to Z given an initial level of pollution Z^0 and an initial allocation of pollution emissions ξ_j^0 for $j \in J$ is therefore:

$$C^A(Z) = \sum_{j\in J}\left[\int_{\xi_j Z}^{\xi_j^0 Z^0} MC_j^A dZ_j\right] \tag{20}$$

which implies that the welfare cost as a share of national income is given by (see Appendix):

$$\frac{C^A}{R} = \frac{\left(\sum_{j\in J}\alpha_j\beta_j\Gamma_j\right)\left(\ln(Z^0/Z)\right) + \left(\sum_{j\in J}\alpha_j\beta_j\Gamma_j\left(\ln(\xi_j^0/\xi_j)\right)\right)}{\left(1 + \sum_{j\in J}\frac{\beta_j}{\sigma_j - 1}\right)} \tag{21}$$

Result 4. Aggregate Welfare Cost of Regulations:Holding pollution shares constant, the welfare cost of regulations is proportional to the percentage change (log change) in pollution. When pollution shares are reallocated, regulations generate an additional cost (savings) associated with reallocating the pollution shares across sectors that is independent of the level of pollution reductions.

Proof. Follows from (21). □

Result 4 demonstrates that reallocating pollution shares across sectors to a more efficient allocation shifts the cost of a program of emissions reductions down, but does not bear on the marginal cost of additional emissions reductions. Holding pollution shares constant, the marginal abatement cost is the following:

$$MC^A = -\frac{dC^A}{dZ} = \frac{R}{Z}\frac{\sum_{j\in J}\alpha_j\beta_j\Gamma_j}{\left(1 + \sum_{j\in J}\frac{\beta_j}{\sigma_j - 1}\right)} \tag{22}$$

While the assumption that pollution shares are held constant might appear restrictive, this is consistent with both a uniform tax policy and a cost-effective policy.

Corollary 4.1. *The aggregate welfare cost of regulations is proportional to the direct cost, where the proportionality factor is*

$$\frac{\sum_{j\in J}\alpha_j\beta_j\Gamma_j}{\sum_{j\in J}\alpha_j\beta_j} > 1 \tag{23}$$

Expression (21) also corroborates that the cost savings are maximized (welfare cost is minimized) when the allocation of pollution across sectors satisfies (19). The extent of the savings depends on the degree of pollution misallocation across sectors.

2.6. *Pollution damages and second-best policy*

Because regulations generate indirect welfare effects, second-best environmental policy should take these effects into account when determining the optimal amount of pollution.[20] That is, regulations should equate the marginal damage of

[20] Of course, efficiency could be achieved if policymakers had additional policy instruments to control entry-exit decisions, such as a lump-sum entry subsidy, and to restore marginal-cost pricing, such as an output subsidy. Due to numerous practical difficulties of implementation (Dixit and Stiglitz, 1977), I assume that policy is constrained to second-best optimal.

pollution with the marginal abatement cost derived in the previous section.

For tractability, I assume the following functional form governing pollution damages:

$$\psi(Z) = (1 - \zeta Z) \tag{24}$$

where ζ is a constant damage parameter. Expression (24) implies that the consumer's marginal-willingness-to-pay for pollution reductions (or marginal benefit of abatement) is given by:

$$MB^A = -\frac{1}{\lambda}\frac{dW}{dZ} = \frac{\zeta R}{(1-\zeta Z)\left(1 + \sum_{j\in J}\frac{\beta_j}{\sigma_j - 1}\right)} \tag{25}$$

where λ is the marginal utility of income.[21] The second-best pollution level should equate the marginal abatement cost and the marginal benefit of aggregate abatement. That is,

$$MC^A = MB^A \Rightarrow Z^* = \frac{\sum_{j\in J}\alpha_j\beta_j\Gamma_j}{\zeta\left(1 + \sum_{j\in J}\alpha_j\beta_j\Gamma_j\right)} \tag{26}$$

where Z^* is the second-best pollution level. Next, I compare the second-best level of pollution derived in (26) with the level of pollution that would be achieved by equating marginal damages with only the direct cost of regulations $Z^\dagger$. That is,

$$\frac{Z^*}{Z^\dagger} = \left(\frac{\sum_{j\in J}\alpha_j\beta_j\Gamma_j}{\sum_{j\in J}\alpha_j\beta_j}\right)\left(\frac{1 + \sum_{j\in J}\alpha_j\beta_j}{1 + \sum_{j\in J}\alpha_j\beta_j\Gamma_j}\right) \tag{27}$$

The advantage of the specific functional form (24) is that it is possible to compare optimal pollution levels irrespective of pollution damages, which is expedient because marginal damages are not well-established in many instances. The following result sheds light on the role of indirect effects on optimal pollution.

Result 5. Second-Best Pollution Emissions:Accounting for indirect effects of regulations increases the second-best pollution level.

Proof. Expression (27) implies $Z^* > Z^\dagger$ whenever $\Gamma_j > 1$. □

Because the direct cost of regulations understates the true welfare cost, accounting for indirect effects increases the second-best optimal pollution level under general conditions.[22] A corollary of Result 5 is that accounting for indirect effects decreases second-best pollution taxes. In particular, under a uniform-tax policy, the ratio of tax rates that corresponds to the pollution ratio in (27) is simply the inverse of the pollution ratio (that is, $\tau^*/\tau^\dagger = Z^\dagger/Z^* < 1$).

At the industry level, accounting for indirect effects increases the second-best pollution by the same extent as aggregate pollution whenever pollution shares are held constant (recall that industry pollution shares are constant under cost-effective and uniform tax policies). If pollution shares are changed then industry-level pollution would be affected by the change in the allocation of pollution across industries, as well as a change in aggregate pollution. For concreteness, let Z_j^* be the industry-level, cost-effective pollution level when aggregate pollution is Z^*, and $Z_j^\dagger$ be the pollution level resulting from a uniform tax policy when aggregate pollution is $Z^\dagger$. The ratio $Z_j^*/Z_j^\dagger$ is given by:

$$\frac{Z_j^*}{Z_j^\dagger} = \left(\frac{\Gamma_j}{\eta_j}\right)\left(\frac{\sum_{j\in J}\alpha_j\beta_j\eta_j}{\sum_{j\in J}\alpha_j\beta_j}\right)\left(\frac{1 + \sum_{j\in J}\alpha_j\beta_j}{1 + \sum_{j\in J}\alpha_j\beta_j\Gamma_j}\right) \tag{28}$$

In this case, industry-level pollution might decrease despite an overall increase in aggregate pollution due to an increase in the cost-effective allocation of pollution. Similar to above, the corresponding tax ratios are the inverse of pollution ratios (that is, $\tau_j^*/\tau_j^\dagger = Z_j^\dagger/Z_j^*$).

2.7. Generalization: technology upgrading

This section extends the model to account for endogenous abatement-technology upgrading. To conserve on space, only the set up of the model is presented, and Appendix C provides more details and demonstrates that the results are robust to the generalization. That is, while introducing a technology upgrade would bear on various levels of the outcomes (such as welfare), the comparative-static results are unchanged.

Consider an abatement-technology upgrade that reduces emissions by a fixed fraction $1 - \gamma_j \in (0, 1)$, implying that actual emissions are $\gamma_j z$, where z reflects the counterfactual level of emissions for a given amount of labor and pollution abatement given by (4). An example would be an air-pollution scrubber system that removes a fraction of particulates that otherwise

[21] The derivation of λ is provided in Appendix C (see proof of Eq. (17)).

[22] Appendix C demonstrates that Result 5 holds under the weaker assumption of convex pollution damages ($d\psi/dZ < 0$ and $d^2\psi/dZ^2 \leq 0$).

would be released. From the perspective of firm cost, it is straightforward that the reduction in emissions associated with the upgrade is tantamount to an equal (on a percentage basis) reduction in the per-unit cost of pollution. For notation, let the superscript u represent upgrading variables, implying that $c_j^u = A_j(\tau_j\gamma_j)^{\alpha_j}$ or equivalently $c_j^u/c_j = \gamma_j^{\alpha_j} < 1$.

Firms investing in the upgrade incur an additional fixed cost $c_j f_j \Delta_j^c$, where $\Delta_j^c > 0$ is the percentage increase in fixed production cost, and invest in the upgrade only if the additional revenue less variable cost exceeds the additional fixed cost. Because additional fixed cost is identical across firms but additional revenue less variable cost is increasing in firm productivity (that is, the scale of production), more productive firms will always invest in the technology upgrade before less productive firms. In particular, there will exist a threshold productivity $\phi_j^u \geq \phi_j^*$ such that firms will invest in the upgrade if and only if $\phi \geq \phi_j^u$. The following result summarizes the key implications of the generalization, and the remainder of the details are provided in Appendix C.

Result 6. Technology Upgrading Generalization:Results 1 – 5 hold after accounting for endogenous abatement-technology upgrading.

Proof. See Appendix C. □

3. Numerical model

This section numerically simulates the model to the United States manufacturing sector in 1990 using structural parameters estimated by Shapiro and Walker (2015).[23] Pollution emissions are aggregate tons of criteria air pollutants: CO, NO_x, PM_{10}, $PM_{2.5}$, SO_2, and VOCs. Shapiro and Walker (2015) estimate the elasticity of emissions intensity with respect to pollution abatement α_j using plant-level data on pollution emissions and abatement expenditures; the shape parameter of the Pareto distribution k_j using firm-level data on sales; and the elasticity of substitution across varieties σ_j using industry-level data on factor costs and industry revenue.[24] Consequently, the parameters can be interpreted as structural parameters and hence are portable to the present model. In addition to the above parameters, abatement costs also depend on the ratio of pollution emissions to expenditures, and the numerical model uses industry-level ratios of tons of emissions to the value of shipments in 1990 reported by Shapiro and Walker (2015) as the “baseline” level of pollution (that is, the level of pollution such that abatement is zero).

Table A1 in Appendix A reports the elasticity of substitution σ_j and shape parameter k_j, as well as the corresponding composite parameter Γ_j, by industry. Moreover, Fig. B1 in Appendix B plots the elasticity of substitution σ_j and the shape parameter k_j for manufacturing industries, and contour lines are added that correspond to constant values of Γ_j. Table A1 and Fig. B1 corroborate the assumption that $k_j > \sigma_j - 1$, as well as $\sigma_j > 1$.

Table 1 reports marginal abatement costs by industry (excluding the bottom row). In particular, “Overall” refers to marginal abatement cost, while “Cost” and “Indirect” refer to the cost associated with the direct cost effect and the indirect (average-productivity and variety) effects, respectively, as described in Result 3. Table A1 further divides Indirect according to costs associated with average-productivity and variety effects, which are labelled “Avg-Prod,” and “Variety,” respectively. Overall ranges from \$144 to \$193 per ton of pollution, while Cost ranges from \$133 to \$184. Consistent with Corollary 3.1, Indirect is positive for all industries, implying that Overall exceeds Cost for all industries. Moreover, Overall/Cost refers to the ratio of Overall to Cost, which ranges from 1.03 to 1.20, implying that true marginal abatement costs are between 3% and 20% greater than the direct cost. Finally, the ratio $Z^*/Z^\dagger$ sheds light on the role of reallocating pollution shares to achieve cost-effectiveness and accounting for direct and indirect welfare effects (see the corresponding expression (28)). The Table indicates that accounting for indirect effects of regulations and reallocating pollution shares to minimize aggregate abatement cost changes the optimal level of pollution by between -1% and 32%.

The bottom row of Table 1 reports aggregate marginal abatement costs for all manufacturing industries. At the aggregate level, Overall is \$159 and Cost is \$146, implying that Indirect is \$13, and the ratio of Overall to Cost is 1.09. Finally, accounting for the indirect effects of regulations increases second-best pollution by 9% (see the corresponding expression (27)).

Fig. 1 plots marginal abatement cost functions for two representative industries: Paper and Publishing, and Chemicals. The blue dot-dashed line is Cost, the red dashed line is the sum of Cost and Avg-Prod, and the black solid line is Overall (sum of Cost, Avg-Prod, and Variety). These industries are selected because they are among the more pollution intensive industries and because their Overall costs are dissimilar. The Figure demonstrates that, while the Paper/Publishing and Chemicals industries have similar Cost, the Paper/Publishing Industry has a lower Overall because the Avg-Prod is larger in magnitude and Variety is smaller in magnitude. The marginal abatement cost curves for other industries are provided in Fig. B2 in Appendix B.

Table A2 in Appendix A reports the aggregate marginal abatement cost for various levels of pollution reductions, holding

[23] Shapiro and Walker (2015) estimate the parameters for single year 1990 because it is the only year in which all of the necessary data are available. For consistency, values are reported in 1990 dollars. More details regarding the estimated parameters are provided by Shapiro and Walker (2015).

[24] Pollution emissions data are from the Environmental Protection Agency's National Emissions Inventory and pollution abatement cost data are from the Pollution Abatement Cost and Expenditures survey.

Table 1
Marginal Abatement Cost.

	Marginal Abatement Cost				
	Overall	Cost	Indirect	$\frac{\text{Overall}}{\text{Cost}}$	$Z^*/Z^{\dagger}$
Food, Beverages, Tobacco	171.50	149.06	22.44	1.15	1.18
Textiles, Apparel, Fur, Leather	158.87	148.13	10.74	1.07	1.09
Wood Products	151.81	140.31	11.50	1.08	1.04
Paper and Publishing	159.47	154.82	4.65	1.03	1.09
Coke, Refined Petroleum, Fuels	143.83	132.91	10.92	1.08	0.99
Chemicals	181.62	151.80	29.82	1.20	1.25
Rubber and Plastics	161.42	149.55	11.87	1.08	1.11
Other Non-metallic Minerals	173.71	160.70	13.01	1.08	1.19
Basic Metals	148.56	138.35	10.21	1.07	1.02
Fabricated Metals	159.74	147.00	12.74	1.09	1.10
Machinery and Equipment	165.10	153.56	11.54	1.08	1.13
Office, Computing, Electrical	156.03	150.23	5.80	1.04	1.07
Radio, Television, Communications	160.74	155.90	4.85	1.03	1.10
Medical, Precision, and Optical	193.05	183.75	9.30	1.05	1.32
Motor Vehicles, Trailers	153.58	149.48	4.10	1.03	1.05
Other Transport Equipment	170.09	163.32	6.76	1.04	1.17
Furniture, Other, Recycling	171.83	149.24	22.59	1.15	1.18
All Manufacturing	159.14	145.74	13.40	1.09	1.09

NOTES.—Pollution is tons of criteria air pollutants: CO, NO_x, PM_{10}, $PM_{2.5}$, SO_2, and VOCs. Calculations are based on 1990 industry-level ratios of pollution to revenue.

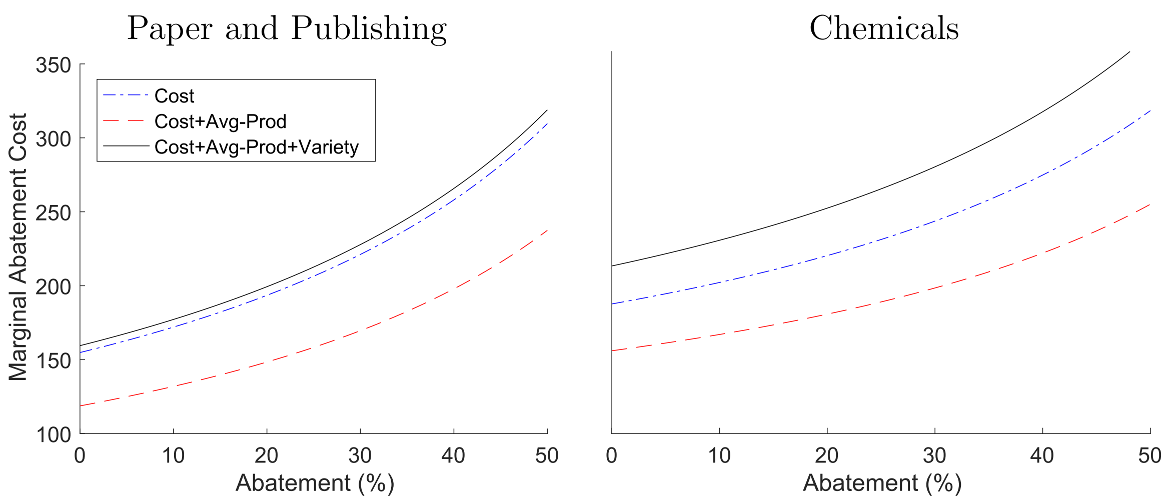

Fig. 1. Marginal Abatement Cost by Industry. *NOTES.*—Pollution is tons of criteria air pollutants: CO, NO_x, PM_{10}, $PM_{2.5}$, SO_2, and VOCs. Calculations are based on 1990 industry-level ratios of pollution to revenue.

pollution shares constant across industries, disaggregated according to the effects described in Result 3. Overall is $159 at baseline levels of pollution, increasing to $188 after reducing pollution by 15%, and increasing to $232 after reducing pollution by 30%, while Cost is $146 at baseline levels of pollution, increasing to $172 after reducing pollution by 15%, and increasing to $212 after reducing pollution by 30%. Table A2 also reports Indirect abatement costs, which are further divided according to Avg-Prod and Variety, for various levels of pollution reductions. Column 6 reports the average cost for various levels of pollution reductions, while Column 7 reports the average cost for various levels of pollution reductions when

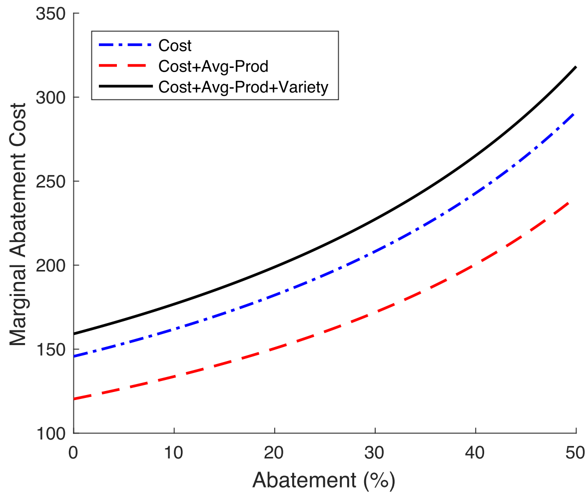

Fig. 2. Aggregate Marginal Abatement Cost. *NOTES.*—Pollution is tons of criteria air pollutants: CO, NO_x, PM_{10}, $PM_{2.5}$, SO_2, and VOCs. Calculations are based on 1990 baseline industry-level ratios of pollution to revenue.

pollution shares are reallocated to cost-effective allocations of pollution (the details of the calculation are provided in the table notes). Finally, Column 8 reports that the welfare cost savings associated with reallocating pollution shares to an allocation that satisfies the equimarginal principle is approximately $72 million dollars. (Recall Result 4 demonstrates that the cost savings associated with reallocating pollution shares is independent of the level of pollution reductions.)

Fig. 2 in Appendix B plots aggregate marginal abatement cost holding pollution shares constant across sectors. The blue dot-dashed line is Cost, the red dashed line is the sum of Cost and Avg-Prod, and the black solid line is Overall (sum of Cost, Avg-Prod, and Variety). Fig. B3 plots the marginal abatement cost (black solid line), the average cost of abatement holding pollution shares constant (blue dashed line), and the average cost of abatement after reallocating pollution shares to satisfy the equimarginal principle (red dashed line). Because the marginal abatement cost is increasing in abatement, the average cost is increasing but is strictly less than the marginal abatement cost. As expected, the average cost is lower after reallocation pollution shares to achieve cost-effectiveness. Juxtaposing the two average cost curves demonstrates that the cost savings associated with cost-effective abatement allocations are modest in comparison to the cost associated with reducing pollution by 5 or 10 percent, but are not particularly important vis-à-vis the total cost of reducing pollution by 20 or 30 percent as the two curves are nearly identical in this range.

3.1. *Abatement costs by pollutant*

Abatement costs in the previous section are based on total tons of criteria air pollutants. This section reports marginal abatement costs by pollutant using pollutant-specific pollution intensities by industry as reported by Shapiro and Walker (2015). In particular, Shapiro and Walker (2015) estimate pollutant-specific parameters by rescaling overall pollution intensity according to the corresponding pollution shares of the pollutant by industry. An implication of this approach is that the elasticities of emissions intensities with respect to abatement are constant and independent of the levels of all other pollutants. This may not be realistic in practice as pollutants are often generated simultaneously, and controlling one pollutant is often only possible when controlling others as well. The results of this section should be viewed as tentative due to challenges associated with disentangling abatement costs by pollutant.

Table A3 in Appendix A reports Overall by industry for the six criteria air pollutants. The results demonstrate that there is seemingly wide variation in marginal abatement costs across industries within pollutants as well as across pollutants within industries. While differences in marginal abatement costs across industries within pollutants suggest potential cost savings associated with reallocating abatement, this implication is highly tentative due to the challenges associated with disentangling pollutant-specific abatement costs as described above. Among all industries in the manufacturing sector, Overall marginal abatement costs are $163 for CO, $161 for NO_x, $117 for PM_{10}, $130 for $PM_{2.5}$, $162 for SO_2, and $175 for VOCs.

4. Sensitivity analysis and model discussion

This section investigates the sensitivity of marginal abatement costs with respect to the model's parameters, and discusses the extent to which the results hinge on the particular modelling assumptions.

4.1. Parameter sensitivity

Because the previous analysis is based on estimated parameters, the results of the numerical model entail a degree of imprecision. This section investigates the extent to which the results are sensitive to imprecision in the model's underlying parameters.

To this end, I calculate lower and upper bounds of the 90% confidence intervals for the parameters α_j, σ_j, and k_j, using the standard errors reported by Shapiro and Walker (2015). Table A4 in Appendix A reports Overall marginal abatement costs and the Overall/Cost ratios associated with the upper and lower bounds of the various parameters. The Table indicates that Overall marginal abatement costs are increasing in α_j and exhibit wide variation across the α_j confidence intervals. Among all manufacturing industries, Overall ranges from \$88 to \$231 (at the lower and upper bounds of α_j, respectively). However, the Overall/Cost ratios are independent of α_j and hence do not exhibit variation in α_j. On the other hand, Overall marginal abatement costs and Overall/Cost ratios do not vary significantly across the σ_j and k_j confidence intervals. In particular, Overall marginal abatement costs are increasing in σ_j through the variety effect, but decreasing in σ_j through their effect on the marginal utility of income. Thus, Overall marginal abatement costs are not monotonically related to σ_j across all industries. Among all manufacturing industries, Overall ranges from \$157 to \$162 (at the upper and lower bounds of σ_j, respectively). The Overall/Cost ratios, however, are monotonically decreasing in σ_j, and the ratio ranges from 1.07 to 1.02 among all manufacturing industries. Moreover, Overall marginal abatement costs are monotonically increasing in k_j through the average-productivity effect, Overall ranges from \$158 to \$160 among all manufacturing industries (at the lower and upper bounds of k_j, respectively). Finally, Overall/Cost ratios are monotonically increasing in k_j, and the ratio ranges from 1.08 to 1.10 among all manufacturing industries.

Because Overall marginal abatement costs do not significantly depend on σ_j and k_j, accounting for imprecision associated with α_j (holding σ_j and k_j constant) approximates the imprecision associated with all three parameters simultaneously.[25] On the other hand, the fact that the Overall/Cost ratios do not depend on α_j, suggests a relatively modest degree of imprecision as the ratio is only modestly dependent on σ_j and k_j.

Fig. B4 in Appendix B plots aggregate marginal abatement costs across 99% confidence intervals for α_j, σ_j, and k_j, where the vertical lines indicate 90% confidence intervals (lower and upper 5% bounds). Consistent with Table A4, marginal abatement costs are highly dependent on and increasing in α_j, though both the direct and indirect welfare effects are increasing by the same extent (on a percentage basis). Fig. B4 also corroborates that marginal abatement costs are not significantly dependent on σ_j and k_j.

Finally, while there is no imprecision associated with the share of industry expenditures β_j, the parameter is generally not constant over time. To shed light on year-to-year changes in marginal abatement costs associated with changes in the industry-expenditure composition, Fig. B5 in Appendix B plots marginal abatement costs from 1990 to 2008. The Figure demonstrates that marginal abatement costs (Overall and Indirect) are relatively stable over the period, with a modest increase after 2004, which primarily reflects increased expenditures in dirty industries as a consequence of increases in oil prices (Shapiro and Walker, 2015). These results are, however, tentative as there were presumably other changes over the time period that would bear on marginal abatement cost, such as the pollution-abatement technology (α_j), which are not reflected in the time series.

4.2. Model discussion

To what extent do the results hinge on the particular modelling assumptions? An advantage of the model setup, which employs a conventional set of assumptions, is that the results are tractable and transparent, which would not be afforded to the same extent under a more general set of assumptions. However, the primary conclusions of the analysis are quite general, at least qualitatively. First, regulations generate indirect effects whenever they induce factor reallocations and loss of variety. Second, because the indirect effects are generally dissimilar across industries, equalizing only the direct cost of regulations would not minimize the total welfare cost of achieving a given level of pollution abatement, implying that a uniform emissions fee would not be cost-effective. The remainder of this section discusses the quantitative implications of the primary modelling assumptions.

The Cobb-Douglas production-pollution technology implies that pollution is unit elastic, which in turn implies that regulations do not generate nominal income effects. If pollution is less (more) than unit elastic then an increase in the emissions fee would increase (decrease) pollution expenditures, thereby increasing (decreasing) aggregate income. While an increase in nominal income would (all else constant) increase welfare, an inelastic factor demand would also be associated with less substitutability in production, implying that the direct cost of regulations would be greater. Thus, the indirect cost is increasing, whereas the direct cost is decreasing, in the elasticity of pollution demand.

Similarly, Cobb-Douglas preferences across industries imply that aggregate industry demand is unit elastic and consumption expenditure shares are constant across industries. If aggregate industry demand is less (more) than unit elastic then an increase in the emissions fee, which would raise industry prices, would increase (decrease) industry expenditures, and decrease (increase) expenditures in all other industries. Because greater elasticity of industry demand corresponds to greater substitutability across industries, the welfare cost would be decreasing in the elasticity of industry demand.

Cobb-Douglas technologies and upper-tier preferences are sufficient conditions such that regulations do not generate inter-industry factor reallocations. While inter-industry reallocations might serve to reduce the indirect cost of regulations

[25] Accounting for imprecision associated with all three parameters depends on the covariance of the parameters, which is not reported by Shapiro and Walker (2015).

and narrow the differences in marginal abatement costs across industries, it is not necessarily the case in general. That is, inter-industry reallocations, generated as a consequence of non-unit-elastic demand for (i) pollution or (ii) aggregate industry consumption, are generally unrelated to the sources of variation in the indirect cost of regulations (that is, the elasticity of substitution within industries and the distribution of productivities across industries).

Monopolistic competition models typically employ constant elasticity of substitution (CES) preferences within industries for tractability as it implies that firms charge constant markups. Under variable elasticity of substitution, markups are related to quantities and in turn firm productivity. That is, because more productive firms sell higher quantities, more productive firms would charge higher (lower) markups whenever the elasticity of substitution is negatively (positively) related to quantities. Consequently, because regulations increase cost and in turn reduce output, regulations would bear on firm markups. In particular, if markups are positively (negatively) correlated with quantities then regulations would decrease (increase) firm markups. Moreover, because regulations force the least productive firms to exit the market, an increase in the emissions fee would increase (decrease) average industry markups whenever markups are positively (negatively) correlated with quantity. The former implies that the welfare cost is decreasing, while the latter implies that the welfare cost is increasing, in the extent that markups are positively correlated to quantities.

The Pareto distribution of firm productivities implies that the mass of firms (and varieties) exhibits constant elasticity with respect to the cutoff productivity levels, which in turn exhibits constant elasticity with respect to firm cost. Because the indirect cost of regulations exhibits constant elasticity with respect to the mass of firms, the indirect cost of regulations are proportional to the direct cost of regulations, implying that the welfare cost of regulations are proportional to the direct cost. More generally, if the mass of firms exiting the market (for a given increase in the cutoff productivity) is increasing (decreasing) in the mass of active firms then the indirect cost of regulations would be increasing (decreasing) in the stringency of regulations.

Thus, while the qualitative results hold under a more general set of assumptions, the above discussion highlights that the quantitative results are sensitive to the particular modelling assumptions. For example, while regulations generate indirect costs in general, the constant proportionality of indirect cost to direct cost is dependent on the distribution of firm productivities. Further, income effects and variable markups might generate non-constant indirect welfare effects as well. Therefore, the numerical simulations should be viewed in light of the sensitivity of the quantitative results to the particular modelling assumptions.

Finally, what is the role of international trade? Because it is beyond the scope of this paper, I make several remarks and leave the formal analysis of trade to future research.[26] First, when trade is costless, the outcomes associated with an open economy are identical to those associated with a larger (greater endowment of labor) closed economy (Melitz, 2003). Because the results are invariant with respect to country size, the results would be identical in a bloc of countries (or world) with no trade barriers. Second, trade barriers would generate another distortion in the economy, implying that environmental policy should account for not only the indirect effects emphasized herein, but also effects associated with trade outcomes that bear on welfare.

To gain insight on trade effects, consider a reduction in trade costs in a particular industry. With firm heterogeneity and fixed trade costs, only the most productive firms export. Hence, decreased trade costs would increase the number of exporting firms, while increased trade exposure would force the least productive firms to exit, implying that labor would be reallocated within the industry to more productive firms (Melitz, 2003). Within the industry, increased trade would decrease domestic labor employed in producing domestic goods, but increase labor employed in producing exported goods, implying that labor would generally be reallocated across sectors (that is, the two effects would not necessarily cancel). While increased trade would increase welfare, it would also reduce the indirect cost of regulations as the variety effect would be partially offset by increases in foreign varieties. While trade might serve to reduce differences in marginal abatement cost across industries, it is not necessarily the case that increased trade would equalize, or even reduce, differences in marginal abatement cost.[27]

5. Conclusion

This paper developed a multi-sector general equilibrium model to account for the direct cost of regulations and the indirect cost associated with factor reallocations and loss of variety. The model derives an analytical marginal abatement cost function, dividing the cost according to three distinct effects: cost, average-productivity, and variety effects. While the indirect effects are confounding in nature, the model demonstrates that the variety effect exceeds the average-productivity effect, implying that accounting for indirect effects increases the welfare cost of regulations. Moreover, the welfare cost of regulations is proportional to the direct compliance cost, where the proportionality factor is a fixed constant that depends on the elasticity of substitution between product varieties and the shape parameter of the distribution of firm productivities. Finally, the model sheds light on the implications for optimal environmental policy.

The model is numerically simulated using parameters for the U.S. manufacturing sector for criteria air pollutants. The numerical model demonstrates that the marginal abatement cost at current levels of pollution ranges between $144 and $194 per ton of pollution across industries. Consistent with the direct cost of regulations understating the true welfare cost, the indirect cost of regulations ranges between $5 and $30. The aggregate marginal abatement cost is $159 at current levels

[26] Kreickemeier and Richter (2013) investigate the role of trade in pollution emissions in the context of firm heterogeneity and monopolist competition, but that analysis is limited to a single industry and fixed emissions intensities, and does not grapple with welfare effects of regulations.

[27] For example, trade induced factor reallocations might entail increased output and in turn pollution among industries with relatively low abatement cost.

of pollution, increasing to $232 after reducing pollution by 30%.

What conclusions can we draw regarding the welfare cost of regulations? The numerical model indicates that, independent of the amount of abatement undertaken, the welfare cost is approximately 9% greater than the direct compliance cost of regulations for the U.S. manufacturing sector. To put this in perspective, based on economic cost calculated by Greenstone et al. (2012), this implies that the welfare cost of the NAAQS regulations are on the order of $12 billion rather than $11 billion (or $15.6 billion rather than $14.3 billion after correcting for survivorship). While this number might appear to be an important takeaway from this study, I emphasize the more prudent conclusion that the direct burden of regulations belies the true welfare cost, and that the direct burden on regulated firms likely represents a lower bound of the true cost.

What insights does the model provide regarding optimal environmental policy? The model demonstrates that a uniform emissions fee does not satisfy the equimarginal principle and derives the cost-minimizing allocations of pollution across industries (or alternatively the cost-minimizing emissions fees by industry). The numerical model indicates that the efficiency-cost savings of reallocating pollution across industries to satisfy the equimarginal principle is approximately $72 million dollars. While policy makers likely face constraints with respect to the degree to which industries can face differential cost of emissions, the numerical model demonstrates that there are potentially substantial cost savings, even if policies are imperfect or only partially implemented. Finally, accounting for indirect effects of regulations increases the second-best optimal emissions by around 9%.

There are many avenues for future research. To retain tractability and transparency, the model is highly stylized, and future research might extend the model in various ways. For example, it is assumed that factor reallocations are costless, but firm shut down and migration of resources are likely to entail a non-trivial cost. Future research might incorporate these costs, as well as the cost of unemployment to workers, to estimate a more comprehensive measure of the welfare cost of regulations. The model might also be extended more fundamentally to include household labor-leisure decisions and tax distortions from the pre-existing fiscal system. Finally, exploring the welfare costs of regulations is important insofar as it permits a judicious comparison with the benefits of regulations. Future research might use the cost estimates presented in this paper, coupled with estimates of the benefits of regulations, to conduct a cost benefit analysis of the CAAA's, therein shedding light on the optimal stringency of regulations.

Acknowledgements

I thank Till Requate (the Editor) and two anonymous referees for valuable comments and suggestions. I am grateful to Joe Shapiro for providing data, and audience participants at the 2016 Canadian Resource and Environmental Economics Study Group Annual Meeting.

Appendix A. Tables

Table A1
Industry Parameters and Marginal Abatement Cost.

				Marginal Abatement Cost				
Industry	σ	k	Γ	Overall	Cost	Avg-Prod	Variety	Indirect
Food, Beverages, Tobacco	3.79	4.81	1.15	171.50	149.06	−30.99	53.43	22.44
Textiles, Apparel, Fur, Leather	4.87	5.38	1.07	158.87	148.13	−27.53	38.28	10.74
Wood Products	5.94	8.30	1.08	151.81	140.31	−16.90	28.40	11.50
Paper and Publishing	4.80	4.29	1.03	159.47	154.82	−36.09	40.74	4.65
Coke, Refined Petroleum, Fuels	8.18	17.52	1.08	143.83	132.91	−7.59	18.51	10.92
Chemicals	3.28	4.13	1.20	181.62	151.80	−36.76	66.58	29.82
Rubber and Plastics	4.59	5.02	1.08	161.42	149.55	−29.79	41.66	11.87
Other Non-metallic Minerals	3.66	3.39	1.08	173.71	160.70	−47.40	60.41	13.01
Basic Metals	6.66	9.72	1.07	148.56	138.35	−14.23	24.44	10.21
Fabricated Metals	4.77	5.60	1.09	159.74	147.00	−26.25	38.99	12.74
Machinery and Equipment	4.25	4.30	1.08	165.10	153.56	−35.71	47.25	11.54
Office, Computing, Electrical	5.24	5.07	1.04	156.03	150.23	−29.63	35.43	5.80
Radio, Television, Communications	4.66	4.13	1.03	160.74	155.90	−37.75	42.59	4.85
Medical, Precision, and Optical	2.89	2.09	1.05	193.05	183.75	−87.92	97.22	9.30
Motor Vehicles, Trailers	5.62	5.29	1.03	153.58	149.48	−28.26	32.35	4.10
Other Transport Equipment	3.88	3.27	1.04	170.09	163.32	−49.95	56.71	6.76
Furniture, Other, Recycling	3.77	4.77	1.15	171.83	149.24	−31.29	53.88	22.59

NOTES.—Pollution is tons of criteria air pollutants: CO, NO_x, PM_{10}, $PM_{2.5}$, SO_2, and VOCs. Marginal Abatement Costs are based on 1990 industry-level ratios of pollution to revenue. The parameters σ and k are estimated by Shapiro and Walker (2015).

Table A2
Aggregate Marginal Abatement Cost.

	Marginal Abatement Cost					Average Cost		
	Overall	Cost	Avg-Prod	Variety	Indirect	Current	Optimal	Savings (mil)
0%	159.14	145.74	−25.38	38.78	13.40			71.94
1%	160.77	147.23	−25.63	39.17	13.54	159.95	88.63	
2.5%	163.27	149.52	−26.03	39.78	13.75	161.19	132.66	
5%	167.61	153.50	−26.73	40.84	14.11	163.30	149.04	
15%	187.56	171.77	−29.91	45.70	15.79	172.57	167.82	
30%	231.69	212.18	−36.94	56.45	19.51	190.90	188.60	
50%	318.29	291.49	−50.75	77.55	26.80	220.62	219.18	

NOTES.—Pollution is tons of criteria air pollutants: CO, NO_x, PM_{10}, $PM_{2.5}$, SO_2, and VOCs. Calculations are based on 1990 industry-level ratios of pollution to revenue. Savings is Cost Savings (CS) in millions and Optimal Average Cost AC^* is given by $AC^* = AC - CS/(Z^0 - Z)$ where AC is average cost.

Table A3
Marginal Abatement Cost by Pollutant.

	Overall Marginal Abatement Cost by Pollutant					
	CO	NO_x	PM_{10}	$PM_{2.5}$	SO_2	VOCs
Food, Beverages, Tobacco	72.89	222.95	257.25	278.69	197.23	235.81
Textiles, Apparel, Fur, Leather	31.77	153.58	95.32	111.21	158.87	428.96
Wood Products	212.53	94.66	164.31	226.82	76.80	141.09
Paper and Publishing	142.59	198.87	117.26	164.16	196.06	107.88
Coke, Refined Petroleum, Fuels	158.22	143.30	41.02	55.94	196.04	129.98
Chemicals	183.76	251.07	71.58	81.20	141.02	270.30
Rubber and Plastics	32.28	129.13	71.02	87.16	125.90	600.47
Other Non-metallic Minerals	29.14	300.35	557.00	405.70	210.14	50.99
Basic Metals	257.19	59.11	63.75	84.18	129.06	47.97
Fabricated Metals	31.95	127.79	71.88	87.86	103.83	710.83
Machinery and Equipment	156.84	165.10	156.84	198.11	123.82	445.76
Office, Computing, Electrical	202.83	70.21	66.31	81.91	156.03	132.62
Radio, Television, Communications	96.45	96.45	48.22	48.22	128.60	337.56
Medical, Precision, and Optical	12.87	521.23	180.18	283.14	148.00	334.62
Motor Vehicles, Trailers	61.43	168.93	61.43	61.43	184.29	952.17
Other Transport Equipment	25.51	170.09	102.05	102.05	161.58	544.28
Furniture, Other, Recycling	21.48	115.98	103.10	128.87	158.94	674.42
All Manufacturing	162.80	160.98	116.52	129.82	162.28	174.72

NOTES.—Calculations are based on 1990 industry-level ratios of pollution to revenue. Marginal Abatement Costs are based on estimates of pollution elasticities by pollutant provided by Shapiro and Walker (2015).

Table A4
Sensitivity Analysis of Marginal Abatement Cost.

	α-sensitivity				σ-sensitivity				k-sensitivity			
	Overall		Overall/Cost		Overall		Overall/Cost		Overall		Overall/Cost	
	<5%	>95%	<5%	>95%	<5%	>95%	<5%	>95%	<5%	>95%	<5%	>95%
Food, Beverages, Tobacco	94.56	248.44	1.15	1.15	170.59	172.11	1.15	1.15	170.06	172.82	1.14	1.16
Textiles, Apparel, Fur, Leather	87.60	230.15	1.07	1.07	157.81	159.65	1.08	1.07	158.00	159.69	1.07	1.08
Wood Products	83.70	219.91	1.08	1.08	152.53	151.05	1.10	1.07	151.22	152.36	1.08	1.09
Paper and Publishing	87.93	231.02	1.03	1.03	160.59	158.32	1.05	1.02	158.03	160.81	1.02	1.04
Coke, Refined Petroleum, Fuels	79.30	208.36	1.08	1.08	146.09	142.27	1.11	1.06	142.42	144.86	1.07	1.09
Chemicals	100.14	263.10	1.20	1.20	183.44	179.75	1.22	1.18	180.41	182.76	1.19	1.20
Rubber and Plastics	89.00	233.83	1.08	1.08	160.63	161.92	1.08	1.07	160.61	162.18	1.07	1.08
Other Non-metallic Minerals	95.78	251.65	1.08	1.08	178.78	169.45	1.12	1.05	171.04	176.11	1.06	1.10
Basic Metals	81.91	215.20	1.07	1.07	156.40	144.32	1.14	1.04	147.24	149.67	1.06	1.08
Fabricated Metals	88.07	231.40	1.09	1.09	158.55	160.64	1.09	1.08	159.27	160.19	1.08	1.09
Machinery and Equipment	91.03	239.16	1.08	1.08	163.89	166.00	1.08	1.07	163.07	166.91	1.06	1.09
Office, Computing, Electrical	86.03	226.02	1.04	1.04	155.12	156.66	1.04	1.04	154.51	157.40	1.03	1.05
Radio, Television, Communications	88.63	232.86	1.03	1.03	159.43	161.77	1.03	1.03	156.94	163.91	1.01	1.05
Medical, Precision, and Optical	106.44	279.66	1.05	1.05	192.08	193.67	1.05	1.05	188.69	197.01	1.03	1.07
Motor Vehicles, Trailers	84.68	222.48	1.03	1.03	152.30	154.57	1.03	1.03	151.90	155.07	1.02	1.04

Table A4 (*continued*)

	α-sensitivity				σ-sensitivity				k-sensitivity			
	Overall		Overall / Cost		Overall		Overall / Cost		Overall		Overall / Cost	
	<5%	>95%	<5%	>95%	<5%	>95%	<5%	>95%	<5%	>95%	<5%	>95%
Other Transport Equipment	93.78	246.39	1.04	1.04	168.88	170.98	1.04	1.04	166.59	173.15	1.02	1.06
Furniture, Other, Recycling	94.74	248.91	1.15	1.15	170.90	172.45	1.16	1.15	171.50	172.15	1.15	1.15
All Manufacturing	87.75	230.54	1.09	1.09	162.07	157.20	1.12	1.07	157.73	160.37	1.08	1.10

NOTES.—Pollution is tons of criteria air pollutants: CO, NO_x, PM_{10}, $PM_{2.5}$, SO_2, and VOCs. Calculations are based on 1990 industry-level ratios of pollution to revenue. Lower and upper bounds of 90% confidence intervals (<5% and >95%) are calculated using standard errors reported by Shapiro and Walker (2015).

Appendix B. Figures

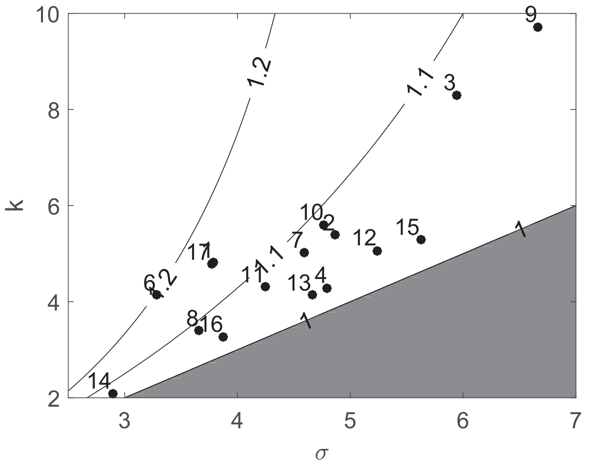

Fig. B1. Γ-isoquant contour lines. *NOTES*.—The figure plots the elasticity of substitution σ and the Pareto shape parameter k for manufacturing sectors. The numbers 1-17 correspond to the ordered industries in Table 1. The set of $(\sigma - k)$ that correspond to a given value of Γ are indicated by the value within the contour lines. The grey shaded area indicates the set of points such that the assumption $k > \sigma - 1$ is violated.

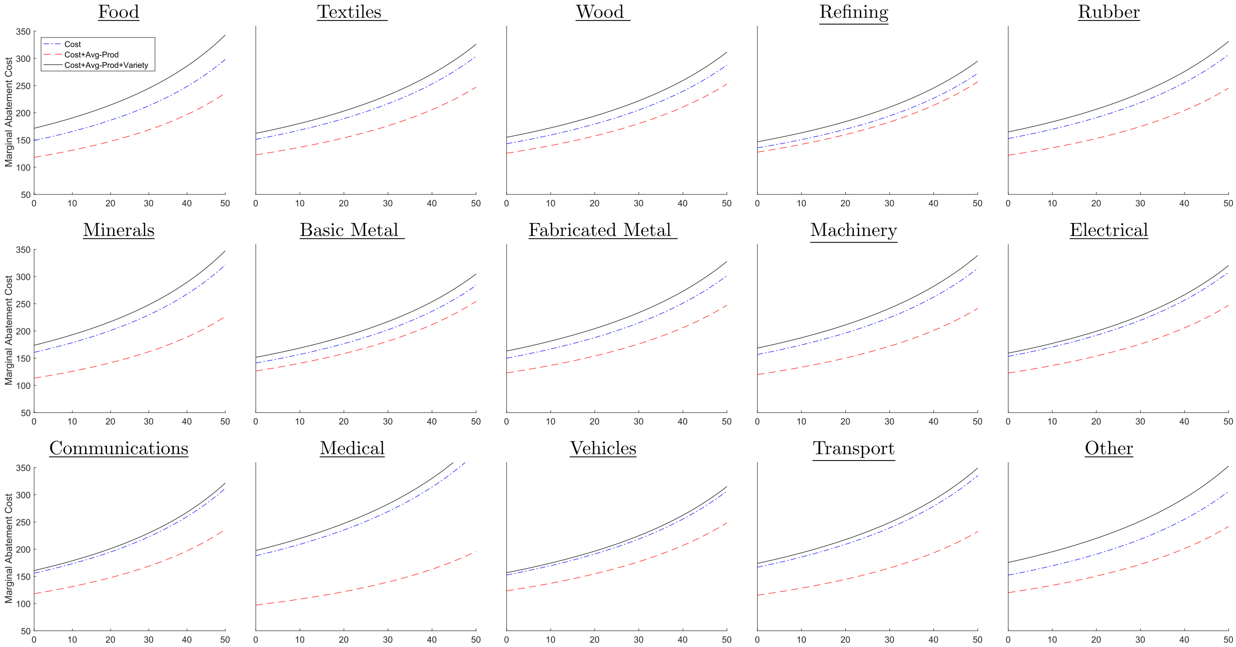

Fig. B2. Marginal Abatement Cost by Industry. *NOTES.*—Pollution is tons of criteria air pollutants: CO, NO_x, PM_{10}, $PM_{2.5}$, SO_2, and VOCs. Calculations are based on 1990 industry-level ratios of pollution to revenue. Industry names are abbreviated to conserve space. See Table A1 for the complete industry name.

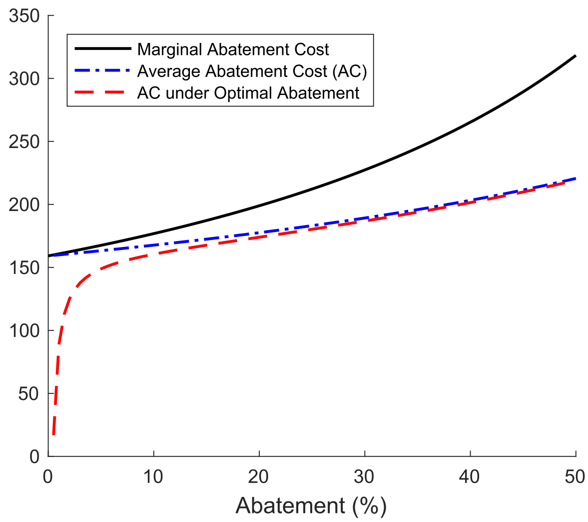

Fig. B3. Aggregate Marginal and Average Abatement Cost. *NOTES.*—Pollution is tons of criteria air pollutants: CO, NO_x, PM_{10}, $PM_{2.5}$, SO_2, and VOCs. Calculations are based on 1990 industry-level ratios of pollution to revenue. Savings is Cost Savings (CS) in millions and Optimal Average Cost AC^* is given by $AC^* = AC - CS/(Z^0 - Z)$ where AC is average cost.

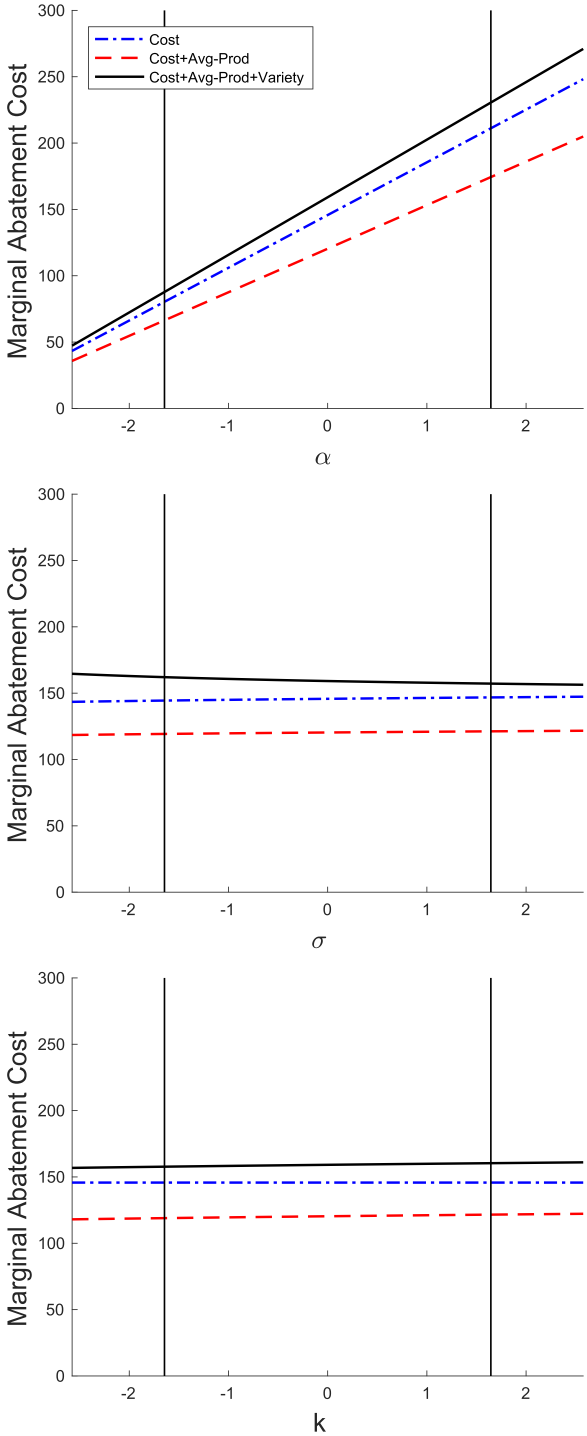

Fig. B4. Aggregate Overall Marginal Abatement Cost Sensitivity. *NOTES.*—Pollution is tons of criteria air pollutants: CO, NO_x, PM_{10}, $PM_{2.5}$, SO_2, and VOCs. Calculations are based on 1990 industry-level ratios of pollution to revenue. The horizontal axes correspond to standard errors of the corresponding parameters, where the vertical lines correspond to the lower and upper bounds of 90% confidence intervals.

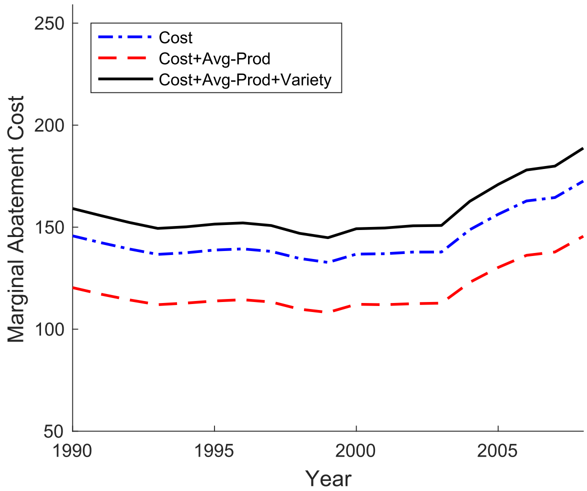

Fig. B5. Marginal Abatement Cost by Year. *NOTES.*—Pollution is tons of criteria air pollutants: CO, NO_x, PM_{10}, $PM_{2.5}$, SO_2, and VOCs. Calculations are based on 1990 industry-level ratios of pollution to revenues. Marginal Abatement Costs are calculated using year-specific expenditure shares provided by Shapiro and Walker (2015).

Appendix C. Proofs

C.1. Proof of Result 1

Using a two-stage budgeting procedure as in Dixit and Stiglitz (1977), consumer demand and expenditures for variety $\omega \in \Omega_j$ are given by:

$$q(\omega) = Q_j\left[\frac{p(\omega)}{P_j}\right]^{-\sigma_j} \quad \text{and} \quad r(\omega) = R_j\left[\frac{p(\omega)}{P_j}\right]^{1-\sigma_j} \tag{29}$$

where $r(\omega) = p(\omega)q(\omega)$ is expenditures on variety $\omega \in \Omega_j$. The aggregate variables P_j and Q_j are aggregate price and quantity indices in sector $j \in J$. That is,

$$P_j = \left[\int_{\omega\in\Omega_j} p(\omega)^{1-\sigma_j} d\omega\right]^{\frac{1}{1-\sigma_j}} \quad \text{and} \quad Q_j = \left[\int_{\omega\in\Omega_j} q(\omega)^{\frac{\sigma_j-1}{\sigma_j}} d\omega\right]^{\frac{\sigma_j}{\sigma_j-1}} \tag{30}$$

Moreover, aggregate expenditures in sector $j \in J$ are $R_j = P_jQ_j = \beta_jR$, where R is the economy's total expenditure (or income).

Recall that profit maximization implies that firms set prices equal to a constant markup over marginal cost, which implies that revenue is given by:

$$r_j(\phi) = R_jP_j^{\sigma_j-1}\left(\frac{c_j}{\phi\rho_j}\right)^{1-\sigma_j} \tag{31}$$

Integrating over all firms implies that expected revenue is given by:

$$\begin{aligned}
\bar{r}_j &= \int_{\phi_j^*}^{\infty} r_j(\phi)\mu_j(\phi)d\phi \\
&= r_j(\phi_j^*)\int_{\phi_j^*}^{\infty} \frac{r_j(\phi)}{r_j(\phi^*)}\mu_j(\phi)d\phi \\
&= r_j(\phi_j^*)\int_{\phi_j^*}^{\infty} \left(\frac{\phi}{\phi_j^*}\right)^{k_j-\sigma_j+1}\left(\frac{k_j}{\phi}\right)d\phi \\
&= r_j(\phi_j^*)\left(\frac{k_j}{k_j-\sigma_j+1}\right)
\end{aligned} \tag{32}$$

The (ZCP) therefore implies that:

$$\bar{r}_j = \sigma_j f_j c_j \left(\frac{k_j}{k_j - \sigma_j + 1} \right) \Rightarrow \bar{\pi}_j = \left(\frac{\sigma_j - 1}{k_j - \sigma_j + 1} \right) f_j c_j \tag{33}$$

Using (33) in the (FE) condition implies that:

$$\phi_j^* = \left[\left(\frac{\sigma_j - 1}{k_j - \sigma_j + 1} \right) \left(\frac{f_j c_j}{\delta_j f_j^e} \right) \right]^{1/k_j} \tag{34}$$

Next, relative output shares are given by:

$$\frac{q_j(\phi)}{q_j(\tilde{\phi}_j)} = \left(\frac{\tilde{\phi}_j}{\phi} \right)^{-\sigma_j} \tag{35}$$

The inverse of the harmonic mean where the weights are the firms' relative output shares is therefore given by:

$$\begin{aligned} \frac{1}{\tilde{\phi}_j} &= \int_{\phi_j^*}^{\infty} \left(\frac{1}{\phi} \right) \left(\frac{\tilde{\phi}_j}{\phi} \right)^{-\sigma_j} \mu_j(\phi) d\phi \\ &= \int_{\phi_j^*}^{\infty} \left(\frac{1}{\phi} \right) \left(\frac{\tilde{\phi}_j}{\phi} \right)^{-\sigma_j} \left(\frac{k_j}{\phi} \right) \left(\frac{\phi_j^*}{\phi} \right)^{k_j} d\phi \\ &= \tilde{\phi}_j^{-\sigma_j} (\phi_j^*)^{\sigma_j - 1} \left(\frac{k_j}{k_j - \sigma_j + 1} \right) \end{aligned} \tag{36}$$

Rearranging terms therefore implies that:

$$\tilde{\phi}_j = \left(\frac{k_j}{k_j - \sigma_j + 1} \right)^{\frac{1}{\sigma_j - 1}} \phi_j^* \tag{37}$$

C.2. Proof of (9)

For notation, let z^q and z^f represent pollution emissions from the variable and fixed components of production, respectively. Expenditures on pollution emissions are therefore:

$$\tau_j z_j(\phi) = \tau_j (z_j^q(\phi) + z_j^f(\phi)) = \alpha_j \left[\rho_j r_j(\phi) + f_j c_j \right] \tag{38}$$

Using that $M_j = R_j / \bar{r}_j$ and integrating over all firms in the sector imply that aggregate pollution expenditures are given by:

$$\tau_j Z_j = \alpha_j \left[\rho_j R_j + M_j f_j c_j \right] = \alpha_j \eta_j \beta_j R \tag{39}$$

where $\eta_j \equiv 1 - (\sigma_j - 1)/(k_j \sigma_j) \in (0, 1)$.

C.3. Proof of footnote 18

In this proof, it is demonstrated that industry-level labor used in entry, fixed production, and variable production are given by:

$$\frac{L_j^e}{L_j} = \frac{\rho_j}{k_j(1 - \alpha_j \eta_j)}, \quad \frac{L_j^f}{L_j} = \frac{(1 - \alpha_j)(k_j - \sigma_j + 1)}{k_j \sigma_j (1 - \alpha_j \eta_j)}, \quad \frac{L_j^q}{L_j} = \frac{\rho_j (1 - \alpha_j)}{(1 - \alpha_j \eta_j)} \tag{40}$$

Similar to (39), industry-level variable and fixed labor are given by:

$$L_j^q + L_j^f = (1 - \alpha_j) \left[\rho_j R_j + \left(\frac{k_j - \sigma_j + 1}{k_j \sigma_j} \right) R_j \right] \tag{41}$$

Next, Eqs. (10) and (11) imply the following:

$$R_j = \frac{L_j}{1 - \alpha_j \eta_j} \tag{42}$$

which implies that:

$$\frac{L_j^f}{L_j} = \frac{(1-\alpha_j)(k_j-\sigma_j+1)}{k_j\sigma_j(1-\alpha_j\eta_j)} \quad \frac{L_j^q}{L_j} = \frac{\rho_j(1-\alpha_j)}{(1-\alpha_j\eta_j)} \tag{43}$$

Finally, industry-level labor used in entry is given by:

$$\frac{L_j^e}{L_j} = 1 - \frac{L_j^f}{L_j} - \frac{L_j^q}{L_j} = \frac{\rho_j}{k_j(1-\alpha_j\eta_j)} \tag{44}$$

C.4. Proof of Result 2

The mass of firms can be expressed as $M_j = R_j/\bar{r}_j$. Eqs. (10) and (33) therefore imply the Result 2.

C.5. Proof of (17)

Expression (39) implies that sector-level pollution is given by:

$$Z_j = \frac{\alpha_j\eta_j\beta_j R}{\tau_j} \tag{45}$$

Expression (13) implies that the marginal utility of income (holding aggregate pollution constant) is given by:

$$\lambda = \frac{dW}{dR} = \frac{W}{R}\frac{dU/U}{dR/R} = \frac{W}{R}\left(1 + \sum_{j\in J}\frac{\beta_j}{\sigma_j - 1}\right) \tag{46}$$

Differentiating (45) with respect to τ_j and using (15) imply that:

$$MC_j^A = -\frac{1}{\lambda}\frac{dW/d\tau_j}{dZ_j/d\tau_j} = \left(\frac{R}{Z_j}\right)\frac{\alpha_j\beta_j\Gamma_j}{\left(1 + \sum_{j\in J}\frac{\beta_j}{\sigma_j-1}\right)} \tag{47}$$

Next, I demonstrate that marginal abatement costs are identical under linear damages. To this end, suppose that

$$W = U - \psi Z \tag{48}$$

where $\psi \geq 0$ is a constant damage parameter. Expression (48) implies that the marginal utility of income (holding aggregate pollution constant) is given by:

$$\lambda = \frac{dW}{dR} = \frac{U}{R}\frac{dU/U}{dR/R} = \frac{U}{R}\left(1 + \sum_{j\in J}\frac{\beta_j}{\sigma_j - 1}\right) \tag{49}$$

Differentiating (48) with respect to τ_j implies that

$$\frac{dW}{d\tau_j} = \frac{U}{\tau_j}\frac{dU/U}{d\tau_j/\tau_j} = \frac{U}{\tau_j}\left(\alpha_j\beta_j\Gamma_j\right) \tag{50}$$

Similar to (47),

$$MC_j^A = -\frac{1}{\lambda}\frac{dW/d\tau_j}{dZ_j/d\tau_j} = \left(\frac{R}{Z_j}\right)\frac{\alpha_j\beta_j\Gamma_j}{\left(1 + \sum_{j\in J}\frac{\beta_j}{\sigma_j-1}\right)} \tag{51}$$

C.6. Proof of (21)

Using expression (17) implies that:

$$\begin{aligned}\frac{C^A(Z)}{R} &= \sum_{j\in J}\left[\int_{\xi_j Z}^{\xi_j^0 Z^0}\frac{MC_j^A}{R}dZ_j\right]\\ &= \frac{\sum_{j\in J}\left[\int_{\xi_j Z}^{\xi_j^0 Z^0}\frac{\alpha_j\beta_j\Gamma_j}{Z_j}dZ_j\right]}{\left(1+\sum_{j\in J}\frac{\beta_j}{\sigma_j-1}\right)}\\ &= \frac{\sum_{j\in J}\alpha_j\beta_j\Gamma_j\left[\ln(\xi_j^0 Z^0)-\ln(\xi_j Z)\right]}{\left(1+\sum_{j\in J}\frac{\beta_j}{\sigma_j-1}\right)}\\ &= \frac{\left(\sum_{j\in J}\alpha_j\beta_j\Gamma_j\right)\left(\ln(Z^0/Z)\right)+\left(\sum_{j\in J}\alpha_j\beta_j\Gamma_j\left(\ln(\xi_j^0/\xi_j)\right)\right)}{\left(1+\sum_{j\in J}\frac{\beta_j}{\sigma_j-1}\right)}\end{aligned} \tag{52}$$

C.7. Proof of Result (5)

Under the weaker assumption of convex damages $\psi(Z)$, the marginal benefit of abatement is given by:

$$MB^A = \frac{d\psi}{dZ}\frac{R/\psi}{\left(1+\sum_{j\in J}\frac{\beta_j}{\sigma_j-1}\right)} \tag{53}$$

Again, second-best policy implies equating the marginal cost and marginal benefit of aggregate abatement, implying that:

$$Z^* = \frac{\psi\left(\sum_{j\in J}\alpha_j\beta_j\Gamma_j\right)}{-d\psi/dZ} \tag{54}$$

On the other hand, equating only the marginal benefit with only the direct marginal cost implies that:

$$Z^\dagger = \frac{\psi\left(\sum_{j\in J}\alpha_j\beta_j\right)}{-d\psi/dZ} \tag{55}$$

For contradiction, assume that $Z^* < Z^\dagger$. Then $\psi(Z^*) > \psi(Z^\dagger)$ and $\frac{d\psi(Z^*)}{dZ} \geq \frac{d\psi(Z^\dagger)}{dZ}$, implying that:

$$\frac{Z^\dagger\frac{d\psi(Z^\dagger)}{dZ}}{\psi(Z^\dagger)} > \frac{Z^*\frac{d\psi(Z^*)}{dZ}}{\psi(Z^*)} \tag{56}$$

Using Eqs. (54) and (55), the above inequality implies that

$$\sum_{j\in J}\alpha_j\beta_j > \sum_{j\in J}\alpha_j\beta_j\Gamma_j \tag{57}$$

This is however a contradiction as $\Gamma_j > 1$.

C.8. Proof of Result (6)

The following condition defines the productivity threshold for upgrading:

$$\frac{\Delta_j^r r(\phi_j^u)}{\sigma_j} = f_j c_j \Delta_j^c \tag{58}$$

where $\Delta_j^r = \gamma_j^{\alpha_j(1-\sigma_j)} - 1 > 0$ is the percentage increase in revenue. Eq. (58) implies that the additional revenue less additional variable inputs costs from upgrading exactly equals the additional fixed cost for a firm with the threshold productivity ϕ_j^u.

With productivity distributions of active firms being Pareto, the distribution of upgrading firms ((conditional on being active) is Pareto distributed with support over $[\phi_j^u, \infty)$. That is,

$$\mu_j^u(\phi) = \begin{cases}\frac{k_j}{\phi}\left(\frac{\phi_j^u}{\phi}\right)^{k_j} & \text{if } \phi \geq \phi_j^u\\ 0 & \text{if} \phi < \phi_j^u\end{cases} \tag{59}$$

The probability that a firm upgrades, conditional on being active, is therefore related to the ratio of the threshold productivities. More precisely, if $\upsilon_j \in (0, 1)$ is defined as the probability that an active firm upgrades then $\upsilon_j = (\phi_j^* / \phi_j^u)^k$. Eqs. (31), (ZCP) and (58) solve for the ratio of productivity thresholds. That is, the probability of upgrading is a function of the ratio of additional revenue to additional fixed cost:

$$\upsilon_j = \left(\frac{\Delta_j^r}{\Delta_j^c}\right)^{\frac{k_j}{\sigma_j - 1}} \tag{60}$$

The free entry condition is unchanged, with the exception that expected profits include the potential for upgrading.

Revenue of a firm investing in the upgrade is

$$r_j^u(\phi) = R_j P_j^{\sigma_j - 1}\left(\frac{c_j^u}{\phi \rho_j}\right)^{1-\sigma_j} \tag{61}$$

The additional revenue associated with upgrading r_j^a is therefore given by:

$$r_j^a(\phi) = r_j^u(\phi) - r_j(\phi) = \Delta_j^r r_j(\phi) \tag{62}$$

where $\Delta_j^r = \gamma_j^{\alpha_j(1-\sigma_j)} - 1$. Expected additional revenue conditional on upgrading $\bar{r}_j^a$ is defined as follows:

$$\bar{r}_j^a = \int_{\phi_j^u}^{\infty} r_j^a(\phi)\mu^u(\phi)d\phi \tag{63}$$

Using a procedure similar to (33) implies that:

$$\bar{r}_j^a = r_j^a(\phi_j^u)\left(\frac{k_j}{k_j - \sigma_j + 1}\right) \tag{64}$$

Eq. (58) therefore implies that:

$$\bar{r}_j^a = \sigma_j f_j c_j \Delta_j^c \left(\frac{k_j}{k_j - \sigma_j + 1}\right) \tag{65}$$

Expected profits are therefore equal to the sum of baseline revenue less baseline cost (variable and fixed) and additional revenue less additional cost (variable and fixed) multiplied by the conditional probability of upgrading. That is,

$$\bar{\pi}_j = \left(\frac{\bar{r}_j}{\sigma_j} - c_j f_j\right) + \upsilon_j\left(\frac{\bar{r}_j^a}{\sigma_j} - c_j f_j \Delta_j^c\right) = \left(\frac{\sigma_j - 1}{k_j - \sigma_j + 1}\right) f_j c_j (1 + \upsilon_j \Delta_j^c) \tag{66}$$

where $f_j c_j (1 + \upsilon_j \Delta_j^c)$ is (ex-ante) expected fixed production cost.

Substitution of Eq. (66) in the free entry condition (FE) implies that:

$$\phi_j^* = \left[\left(\frac{\sigma_j - 1}{k_j - \sigma_j + 1}\right)\frac{f_j c_j (1 + \upsilon_j \Delta_j^c)}{\delta_j f_j^e}\right]^{1/k_j} \tag{67}$$

Let $\omega_j(\phi)$ be relative output shares for firms with productivity $\phi_j < \phi_j^u$. Then relative output shares of upgrading firms are $\omega_j^u(\phi) = \omega_j(\phi)(\gamma_j)^{-\alpha_j \sigma_j}$ for firms with productivity $\phi_j \geq \phi_j^u$. Because relative output shares are a continuous function everywhere except the point ϕ_j^u, the harmonic mean of productivity is the following two-part integral:

$$\frac{1}{\tilde{\phi}_j} = \int_{\phi_j^*}^{\phi_j^u}\left(\frac{1}{\phi}\right)\omega_j(\phi_j)\mu_j(\phi)d\phi + \int_{\phi_j^u}^{\infty}\left(\frac{1}{\phi}\right)\omega_j^u(\phi_j)\mu_j(\phi)d\phi \tag{68}$$

Next, we can add (to the first term) and subtract (from the second term) $\int_{\phi_j^u}^{\infty}\left(\frac{1}{\phi}\right)\omega_j(\phi_j)\mu_j(\phi)d\phi$, implying that:

$$\frac{1}{\tilde{\phi}_j} = \int_{\phi_j^*}^{\infty}\left(\frac{1}{\phi}\right)\omega_j(\phi_j)\mu_j(\phi)d\phi + \left((\gamma_j)^{-\alpha_j\sigma_j} - 1\right)\int_{\phi_j^u}^{\infty}\left(\frac{1}{\phi}\right)\omega_j(\phi_j)\mu_j(\phi)d\phi \tag{69}$$

The first term is simply the inverse of the harmonic mean in the case that no firms upgrade, whereas the second term is the adjustment term to account for a subset of firms upgrading. Using a similar produce to reach Eq. (36) implies the following:

$$\int_{\phi_j^u}^{\infty}\left(\frac{1}{\phi}\right)\omega_j(\phi_j)\mu_j(\phi)d\phi = \tilde{\phi}_j^{-\sigma}(\phi_j^u)^{\sigma_j - 1}\upsilon_j\left(\frac{k_j}{k_j - \sigma_j + 1}\right) \tag{70}$$

Combining this result with (36) implies the following:

$$\tilde{\phi}_j = \left(\frac{k_j}{k_j - \sigma_j + 1}\right)^{\frac{1}{\sigma_j - 1}} \phi_j^* \left(1 + \nu_j^{(k_j-\sigma_j+1)/k_j}(\gamma_j^{-\alpha_j\sigma_j} - 1)\right)^{\frac{1}{\sigma_j - 1}} \tag{71}$$

Eqs. (67) and (71) therefore demonstrate that Result 1 holds.

Firm expenditures on pollution emissions for non-upgrading ($\phi < \phi_j^u$) and upgrading ($\phi \geq \phi_j^u$) firms are the following:

$$\alpha_j\left[\rho_j r_j + f_j c_j\right] \quad \text{or} \quad \alpha_j\left[\rho_j r_j^u + f_j c_j(1 + \Delta_j^c)\right] \tag{72}$$

respectively. Subtracting the first term from the second term implies that pollution expenditures associated with the technology upgrade are

$$\alpha_j\left[\rho_j \Delta_j^r r_j + f_j \Delta_j^c c_j\right] \tag{73}$$

Integrating over all upgrading firms in the industry implies that industry-level additional pollution expenditures are given by:

$$\alpha_j \nu_j M_j\left[\rho_j \Delta_j^r \int_{\phi_j^u}^{\infty} r_j(\phi)\mu_j^u d\phi + f_j c_j \Delta_j^c\right] \tag{74}$$

where the mass of upgrading firms is equal to the probability of upgrading multiplied by the mass of active firms. Using that $r_j = r_j^a/\Delta_j^r$ and Eq. (65) imply that

$$\alpha_j \nu_j M_j f_j c_j \Delta_j^c \left(\frac{k_j(\sigma_j - 1)}{k_j - \sigma_j + 1} + 1\right) \tag{75}$$

Similarly, integrating baseline pollution expenditures over all active firms in the industry implies that industry-level baseline pollution expenditures are given by:

$$\alpha_j M_j f_j c_j \left(\frac{k_j(\sigma_j - 1)}{k_j - \sigma_j + 1} + 1\right) \tag{76}$$

Total industry-level pollution expenditures are the sum of industry-level baseline expenditures and additional expenditures. That is,

$$\alpha_j M_j f_j c_j \left(\frac{k_j(\sigma_j - 1)}{k_j - \sigma_j + 1} + 1\right)\left(1 + \nu_j \Delta_j^c\right) \tag{77}$$

Next, industry-level revenue R_j is given by:

$$R_j = M_j\left[\int_{\phi_j^*}^{\infty} r_j(\phi)\mu_j d\phi + \nu_j \int_{\phi_j^u}^{\infty} r_j^a(\phi)\mu_j^u d\phi\right] \tag{78}$$

Eqs. (33) and (65) therefore imply that the mass of firms is

$$M_j = \frac{R_j}{\left(\frac{k_j}{k_j - \sigma_j + 1}\right)\sigma_j f_j c_j (1 + \nu_j \Delta_j^c)} \tag{79}$$

Substituting (79) in (77) implies that total industry-level pollution expenditures are given by:

$$\alpha_j \eta_j \beta_j R \tag{80}$$

Industry-level pollution expenditures are therefore unchanged (see Eq. (39)). It follows that the total income of the economy and industry expenditures are identical to Eq. (10). Next, the mass of varieties in each sector is given by:

$$M_j = \left(\frac{k_j - \sigma_j + 1}{k_j}\right)\left(\frac{\beta_j R}{\sigma_j f_j c_j (1 + \nu_j \Delta_j^c)}\right) \tag{81}$$

Eq. (81) therefore demonstrates that Result 2 holds.

Because the effects of regulations are identical to firm cost, average productivity, and variety, it follows that Result 3 and Corollary 3.1 hold as well. Moreover, the marginal utility of income is unchanged, implying that the marginal cost of abatement is identical and Result 4 holds. Finally, because the marginal cost of abatement is unchanged, it follows that Result 5 holds.

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