Environmental Policy and Technical Change: Pollution Taxes, Access to Finance, and Firm Absorptive Capacity[*]

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Abstract

Firms respond to higher taxes on air pollution by increasing R&D and hence their capacity to absorb new technology. The R&D response to pollution taxation only appears after the taxes are introduced and is concentrated in sectors with higher pollution intensity and relatively immobile production technologies, suggesting a causal linkage. However, the R&D response is substantially weaker in the firms most likely to face financing constraints; small firms only adjust R&D when they have demonstrated access to external financing. Taxing activities with high environmental costs can encourage technical change, but these policies have heterogeneous effects across different types of firms.

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1 Introduction

The nature of technological change plays a central role in determining how environmental constraints and regulations impact human welfare and economic performance (e.g., Popp, Newell, and Jaffe (2010); Acemoglu, Aghion, Bursztyn, and Hemous (2012); Hassler, Krusell, and Olovsson (2018)). Building on this insight, a prominent theoretical literature explores the growth and welfare implications of policies that direct technical change toward environmentally-friendly production technologies (e.g., Acemoglu, Akcigit, Hanley, and Kerr (2016)). A key idea from this work is that policy action is likely necessary to encourage the adoption of new "clean" technologies, due in part to path dependence in technical change (e.g., Aghion, Dechezleprêtre, Hemous, Martin, and Van Reenen (2016)). With the optimal set of policies, directed technical change has the potential to mitigate climate change risks and other environmental disasters without significantly slowing long-run economic growth.

An important and largely open empirical question concerns the impact environmental policy has on technology absorption at the firm level. We provide novel evidence on this question by exploring how taxes on air pollution affect firm investments in research and development (R&D). We focus on R&D because it is the primary way firms enhance their ability to absorb existing knowledge and advance technical knowhow (e.g., Cohen and Levinthal (1989); Griffith, Redding, and Van Reenen (2004)).[1] We find strong evidence that the firms most affected by higher pollution taxes respond by increasing R&D and hence their absorptive capacity. However, there are important heterogeneities in the extent of this response across firms; in particular, we find a much weaker R&D response among the

[1] R&D is also a key input for developing entirely new innovations. We emphasize the "absorptive capacity" or "second face" of R&D because it is the most plausible micro-level mechanism through which pollution taxes encourage the adoption and development of clean technologies. In particular, the firms most affected by environmental policies in general, and pollution taxes in particular (e.g., firms with dirty, immobile production technologies) are much more likely to drive the demand for new technologies than to be the primary *source* for these innovations. Indeed, the clean technologies need not arise from the same country, much less the same industry or firm. In this way, the mechanism we emphasize is broadly consistent with the pattern of innovation development and diffusion emphasized by the environmental economics literature: factors which encourage firms to expand their ability to adopt cleaner technologies will, in turn, increase the *aggregate* demand for new, cleaner, and more efficient innovations (e.g., Lanjouw and Mody (1996); Kerr and Newell (2003); Söderholm and Klaasen (2007); Höglund-Isakson and Sterner (2009); Hammar and Löfgren (2010)). We find broad support for this idea in a more exploratory analysis of country-level innovative outputs at the end of the paper.

firms most likely to face financing constraints, indicating that financing considerations can influence the effectiveness of environmental policy and extent of directed technical change.

Our main tests focus on how increasing taxes on the emission of sulfur oxides (SO_x) affects firm spending on R&D. We focus on SO_x because, in addition to being a major air pollutant, we have detailed information on SO_x taxes at the country level and SO_x emissions at the industry level, the latter of which we use to sort firms based on how heavily "treated" they are by pollution taxes. We merge OECD data on SO_x taxes by country and year (Botta and Kozluk (2014)) with information on firm-level R&D from the Compustat Global database. To measure cross-industry differences in pollution intensity, we use data from Levinson (2009) on SO_x emissions in US manufacturing industries. The final sample covers around 36,000 firm-year observations in 120 manufacturing industries from 18 countries over 22 years.

We find robust evidence that higher taxes on SO_x emissions are positively related to within-firm changes in R&D spending. Notably, higher SO_x taxes are associated with *differentially* higher rates of R&D in firms located in more pollution-intensive industries. These differential effects indicate causality because firms in pollution-intensive industries are more heavily exposed to (or treated by) the increase in SO_x taxation.[2]

Three other pieces of evidence point to a causal relation between pollution taxes and firm R&D. First, the positive association between pollution taxes and R&D only appears in the years after the initial introduction of the tax, a test which Bertrand and Mullainathan (2003) emphasize as crucial for establishing the casual effects of policy changes. At a minimum, this evidence addresses the potential concern that policymakers only impose higher taxes on old (dirty) production technologies *after* firms have started expanding their ability to absorb new technology. Second, we find no evidence that firms facing higher pollution taxes increase capital spending or their stock of fixed assets; not only is this heterogeneity important for

[2] It is worth noting here that firms in pollution intensive industries tend to be *less* innovative and more immobile compared to firms in other industries. For example, the highest pollution industry in our sample is cement manufacturing, which is clearly not a technology-intensive industry and is particularly geographically immobile (see the discussion in Syverson (2004)). See Table 3 and Ederington, Levinson, and Minier (2005) for broader evidence on the positive association between geographic immobility and pollution intensity across industries.

understanding the mechanisms through which environmental policies affect real activity, but it suggests our pollution tax measure is not merely a proxy for broad changes in investment opportunities, which should impact both R&D and capital accumulation. Third, splitting the sample based on the asset mobility measures in Ederington, Levinson, and Minier (2005) shows that the R&D response to pollution taxation is concentrated in industries with relatively immobile assets. In sectors with mobile assets, not only do higher pollution taxes have little impact on R&D, but these taxes are, if anything, *negatively* associated with fixed assets, as expected if some firms relocate production in response to changes in tax rates.[3]

Next, we consider whether financing considerations influence the R&D response to changes in pollution taxes. These tests are motivated by the evidence in several studies showing that R&D spending is sensitive to the availability of finance (e.g., Hall and Lerner (2010); Brown, Martinsson, and Petersen (2012)). In particular, access to arm's-length financing appears to be especially important for innovation in smaller firms (e.g., Brown, Martinsson, and Petersen (2013); Atanassov (2016)). Using alternative indicators of firm-level financing constraints, including firm size, the *Size-age index* from Hadlock and Pierce (2010), and the *Whited-Wu index* from Whited and Wu (2006), we find that the R&D response to pollution taxes is substantially stronger in the firms less likely to face binding financing constraints. Moreover, access to arm's length financing has an important impact on the extent to which small (or otherwise constrained) firms respond to pollution tax increases. Beyond the relation to the literature on financing innovation, these findings highlight an unappreciated factor that can mitigate the impact environmental policies have

[3]The potential for relocation does not have as much of an impact on the overall innovation response to pollution taxation as one might expect because industries with mobile assets are less pollution intensive to begin with. In this way, our findings are broadly consistent with Jaffe, Peterson, and Stavins (1995), who survey the large literature on the pollution haven effects of environmental regulation and conclude that, although environmental regulation can impose large costs on polluting industries, these costs do not appear to significantly affect patterns of international trade. Other support for this idea appears in Dechezleprêtre, Gennaioli, Martin, Muûls, and Stoerk (2015) and Dechezleprêtre and Sato (2017), who find no evidence that firms move production as environmental regulations tighten, Martin, de Preux, and Wagner (2014a), who find no effect on plant exits or employment losses in the UK manufacturing sector from introducing a carbon tax, and Martin, Muûls, de Preux, and Wagner (2014b), who find that polluting firms do not report plans to relocate or close down plants under the EU emissions trading system (see Martin, Muûls, and Wagner (2016) for a survey of these studies).

on technical change. In addition, they suggest that higher environmental taxes can have unintended effects on the competitive structure of industries, as newer and smaller firms with less internal financial resources may find it harder to compete with larger established (and profitable) firms.[4]

Finally, we provide some exploratory evidence on the aggregate consequences of increasing taxes on SO_x emissions. A logical question is whether the firm-level effects we document – which are concentrated in certain firms and industries – show up in more aggregated measures of innovative activity. In particular, to the extent that firms increase R&D in order to absorb new knowledge and achieve the technical knowhow to adopt new technology, there should be a corresponding increase in the aggregate demand for air pollution abatement technologies. Consistent with this idea, we find a significant positive relation between SO_x taxes and the country's stock of pollution abatement technologies. Notably, these taxes are entirely *unrelated* to patenting in other technology classes, which at least shows that we are not simply capturing a spurious relation between changes in pollution taxes and innovative activity at the country level. Although there are clearly limitations to this country-level analysis, the evidence is broadly consistent with the mechanism we emphasize, and it suggests that this micro-level mechanism can have important aggregate effects on the development of environmentally-friendly technologies.

Our research is among a relatively small number of empirical studies to evaluate how innovative activity responds to environmental policies and regulations. Two of the pioneering studies in this area are Jaffe and Palmer (1997), who find a positive association between environmental compliance expenditures and R&D in US manufacturing industries, and Lanjouw and Mody (1996), who document a positive cross-country relation between environmental regulations and environmental patents. The evidence from this early work is consistent with the idea that more stringent environmental regulations can encourage innovation, though the nature of the data and aggregate level of analysis makes it challenging

[4]In this way, our evidence provides a different perspective on prior evidence on the competitive consequences of more strict environmental regulations. For example, Ryan (2012) provides evidence that stricter environmental regulations in the cement manufacturing industry lead to higher entry costs, and, ultimately, welfare losses. Similarly, List, Millimet, Fredriksson, and McHone (2003) find evidence that new plant births slow in pollution intensive industries in the wake of a tightening of environmental standards.

to draw any definitive conclusions, a point Jaffe and Palmer (1997) emphasize. Moreover, as Jaffe, Newell, and Stavins (2002) discuss, market-based environmental policies (such as pollution taxes) have quite different implications for technology adoption compared to the command and control approaches (such as environmental compliance regulation) that have been studied in prior work.

Our main contribution is to provide the first micro-level evidence we know of linking environmental taxes with technological absorptive capacity. Moreover, our focus on R&D at the firm level uncovers important heterogeneities across different types of firms in the extent to which their innovative activity responds to higher pollution taxes. These heterogeneities are not just important because they help with identification; they also highlight unappreciated factors that can influence the impact environmental policy has on technical change. In particular, we are not aware of any other studies that even discuss – much less document – the importance access to finance has for understanding the effects and incidence of environmental policies with the potential to redirect technical change. This omission is notable given the widespread appreciation of the importance of finance for innovation and economic growth (e.g., King and Levine (1993); Brown, Fazzari, and Petersen (2009); Aghion, Howitt, and Levine (2018)).

Relatedly, our study is relevant for evaluating and modeling the macro-economic consequences of environmental policies (e.g., Calel and Dechezleprêtre (2016); Dechezleprêtre and Sato (2017); Albrizio, Kozluk, and Zipperer (2014); Jaffe, Peterson, and Stavins (1995); Porter and van der Linde (1995)). Most importantly, our findings suggest that the aggregate effects of environmental policy are likely multi-dimensional and at least partially contingent on the institutional environment in which they arise. On the one hand, our findings show that taxing environmental pollutants can encourage the adoption of new technologies, which is broadly consistent with a key theoretical mechanism in the modern literature on endogenous growth under environmental constraints (e.g., Acemoglu, Aghion, Bursztyn, and Hemous (2012); Acemoglu, Akcigit, Hanley, and Kerr (2016); Hassler, Krusell, and Olovsson (2018)). But our evidence on heterogeneous effects across different types of firms suggests that the effectiveness of policies seeking to redirect innovation by taxing existing (dirty) production technologies will depend to some extent on the access firms have to external finance. In this way, our findings suggest that financing considerations should figure more prominently in efforts to understand how policy can induce environmentally-friendly technical change.

Finally, our work is part of an emerging literature on the linkages between finance and the environment. Most of this work focuses on the impact of climate change and other environmental issues on firms and financial markets. For example, Krüger (2015) finds that mandatory disclosure of greenhouse gas emissions on the London Stock Exchange had a positive effect on the market value of the most affected firms, while Dimson, Karakaş, and Li (2015) show that US firms improve accounting performance and governance following successful engagements on environmental and social issues. More broadly, Hong, Li, and Xu (forthcoming) find that financial markets under-react to climate change risks, Bansal, Kiku, and Ochoa (2016) show that increasing global temperature levels carries a positive risk premium in capital markets, and **?** find that homes exposed to sea level rise sell at a substantial and increasing discount to comparable properties. More closely related to our study, Levine, Lin, Wang, and Xie (2018) show that variation in credit supply affects firms' emissions of toxic pollutants. Our study is the first we know of to explore how environmental policies and access to finance affect firm-level investment decisions.

2 Theoretical mechanisms

2.1 Pollution taxes, innovation, and technical change

There are two main channels through which pollution taxes can induce innovation and foster environmentally-friendly technical change: i) the diffusion, or broader adoption, of existing pollution abatement technologies, and ii) the development of entirely new technologies and production techniques. This distinction between channels is important for a firm-level study on the innovation consequences of pollution taxes because the high-pollution firms with the most incentive to *absorb* clean technologies need not be the same firms who *generate* new innovations.[5]

A key factor behind technology absorption at the firm level is investment in R&D. For example, firms can respond to higher pollution taxes by either installing devices that absorb the air pollutants and/or changing the production processes to lower pollutants, both of which often involve the complete re-engineering of production processes (Lanjouw and Mody (1996)). More generally, firms need an internal "absorptive capacity" in order to successfully adopt and use cleaner production technologies. This logic follows the ideas in Cohen and Levinthal (1989) and Cohen and Levinthal (1990) on the "second face" of R&D: firms invest in R&D not only to pursue process or product innovation, but also to develop and maintain their capabilities to exploit and appreciate externally available information. Griffith, Redding, and Van Reenen (2003) endogenize absorptive capacity in an innovation and growth model following Aghion and Howitt (1992) and Aghion and Howitt (1998) and conclude that many studies underestimate the social rate of return on R&D by neglecting its impact on absorptive capacity. Both Griffith, Redding, and Van Reenen (2004) and Jaffe (1986) provide empirical evidence on the importance of firm level R&D investment for absorbing external knowledge and stimulating aggregate innovation.

To the extent that pollution taxes stimulate innovation via the R&D-absorptive capacity channel, the effects should be concentrated in the firms most exposed to the pollution tax. In contrast, to the extent these taxes induce innovation in the form of new technological development, the innovation need not (and likely will not) arise from the most affected (polluting) firms. In fact, environmental innovation differs from other types of innovative processes in the importance of co-operation with external partners such as universities and knowledge intensive technology services firms (e.g., De Marchi (2012); Frey, Iraldo, and Testa (2013)). Moreover, Lanjouw and Mody (1996) find that environmental innovations are often not even developed in the same *country* in which they are being employed.

In one of the first and most influential studies on environmental policy and innovation,

[5]Several studies provide cases and general discussions of the process through which clean technology is diffused and developed, including Jaffe, Newell, and Stavins (2002), Kerr and Newell (2003), Söderholm and Klaasen (2007), Söderholm and Klaasen (2007), Horbach (2008), Rennings, Ziegler, Ankele, and Hoffmann (2006), Sterner and Turnheim (2009), Hammar and Löfgren (2010), Kesidou and Demirel (2012). Figure 2 in Lanjouw and Mody (1996) and Figure 3 in Höglund-Isakson and Sterner (2009) illustrate this process.

Jaffe and Palmer (1997) find evidence that when an industry faces higher costs of complying with environmental regulations there is a significant subsequent increase in R&D expenditures. However, they do not find any evidence that these higher compliance costs lead to more patenting activity in the industry.[6]

2.2 Access to finance and investment in R&D

A key advantage of our focus on the firm-level response to higher pollution taxes is the ability to evaluate heterogeneous effects across firms. Indeed, as we discuss in more detail below, our main identification approach builds on the idea that firms located in high-pollution industries are relatively more exposed to pollution taxes. If our findings are causal, the effects should be *differentially* stronger in these (more heavily treated) firms. In addition, high-pollution firms in industries with immobile production technologies should be particularly sensitive to pollution taxes because they are not only heavily treated by the tax, but they are less able to avoid the tax by moving production to another location.

Beyond these efforts to pin down the causal linkages between pollution taxes and technology absorption, we explore another potentially important factor behind cross-firm differences in the innovation response to pollution taxes: access to finance. There are several reasons why financing considerations may affect how different types of firms adjust absorptive capacity in the face of higher pollution taxes. Most notably, the nature of R&D investment makes it particularly susceptible to financing difficulties. For example, R&D has limited collateral value and suffers from potentially severe asymmetric information problems, which can make it costly (if not prohibitive) for smaller and younger firms to fund R&D from external sources (e.g., Hall (1992); Himmelberg and Petersen (1994); Brown, Martinsson, and Petersen (2012)). Moreover, to the extent that external finance is an option for these types of firms, a number of studies provide evidence suggesting that better access

[6]There is a related literature showing that higher energy prices induce the development of energy-efficient technologies (e.g., Aghion, Dechezleprêtre, Hemous, Martin, and Van Reenen (2016), Hassler, Krusell, and Olovsson (2018), Johnstone, Hascic, and Popp (2010), Lööf and Perez (2018), Newell, Jaffe, and Stavins (1999), Jaffe and Stavins (1995) and Popp (2002)). This literature primarily focuses on the second form of innovation (new technology development) and all but one focus either on technology or energy classes rather than on firms or industries. The exception is Aghion, Dechezleprêtre, Hemous, Martin, and Van Reenen (2016), who find that higher fuel prices induce new technology development in the auto industry.

to market-based financing is particularly important for R&D and innovation (e.g., Brown, Fazzari, and Petersen (2009); Brown, Martinsson, and Petersen (2013); Atanassov (2016)). As a consequence, firms with ample internal cash flow and better access to market-based financing may be better positioned than other firms to respond to higher pollution taxes by investing in R&D.

If these financing considerations do affect the firm R&D response to pollution taxation, there are several important implications which, to our knowledge, have not been discussed in the broad literature on environmental policy and technical change. For example, larger established firms with more internal resources may be best positioned to deal with higher pollution taxes by acquiring clean technologies and adopting new production techniques. If so, increasing taxes on air pollution may have the unintended consequence of substantially altering the competitive landscape of affected industries, unless other policies are introduced simultaneously to foster R&D in younger and smaller firms. Additionally, the mechanisms through which environmental taxes stimulate innovation may work differently in countries with deeper financial markets, suggesting that institutions which facilitate arm's-length contracting and support financial market development may have an unappreciated consequences for how effectively environmental policy encourages the adoption and diffusion of new technologies.

3 Data, measurement, and sample characteristics

3.1 Sample construction

We build our primary sample from Compustat Global. The Compustat database reports standardized financial statement information for publicly listed firms in a broad sample of countries. We focus on non-US firms with fully consolidated financial statements, a primary industry classification in the manufacturing sector, and at least three non-missing R&D observations over the period 1990 to 2012.[7] We require countries to have at least ten

[7]To identify a within firm response to pollution taxes we need a sample of firms who at least semi-regularly report R&D. Our findings are similar if we set any missing R&D values to equal zero.

firms with usable R&D data since we need within-country, across-industry coverage of R&D activity for the empirical tests. We drop firms from the US because we use information from the US to measure cross-industry differences in pollution-intensity, as described below. We also drop firms from industries without any SO_x emissions.[8]

We merge the firm-level data from Compustat with information on time-series changes in air pollution taxes for 18 OECD countries, resulting in a sample of approximately 36,000 firm-years across 18 countries over the period 1990 to 2012. Table A.1 reports observation counts across the countries in the sample. Japan accounts for the most observations (by far), followed by the United Kingdom and Canada. We show later that all our main findings are robust to excluding these countries.

Table 1 defines all the variables we use in the study, and Table 2 reports sample summary statistics.

3.2 Pollution taxes

We collect information on the level of taxes and charges directly applied to the pollution of sulfur oxides (SO_x) from Botta and Kozluk (2014). The Botta and Kozluk (2014) approach provides a categorical "score" for each country-year based on the extent to which SO_x emissions are taxed. The resulting pollution tax variable (*Pollution taxes*) ranges from 0 to 6, with 0 indicating no pollution tax and larger values indicating higher taxes on pollution. By construction, the categorical scores are comparable across countries and over time.[9]

Figure 1 shows how the country-level pollution tax values change over time. There is considerable cross- and within-country variation in *Pollution taxes*. Eight countries tax SO_x pollution, seven of which introduce the tax during the sample period. Denmark and Korea implement the largest changes during the time period, both reaching a value of 6 in *Pollution taxes*. Australia and Canada introduce a relatively low SO_x pollution tax. Spain makes multiple changes over the sample period and Japan has the highest value in *Pollution*

[8] We describe the SO_x pollution data below. Only eight out of 128 industries have zero SO_x pollution. Including these industries has no impact on our findings.

[9] Botta and Kozluk (2014) also provide information on cross-country differences in carbon dioxide, diesel, and nitrogen oxide taxes. We focus on SO_x taxes because we have comprehensive information on industry pollution intensity in SO_x and considerable country-level variation in SO_x taxes over time.

taxes during the entire sample period. Ten countries have zero *Pollution taxes* throughout the sample period.[10]

3.3 Industry characteristics

3.3.1 Pollution intensity

Some of our empirical tests focus on the differential impact higher pollution taxes have on industries with a higher propensity to emit SO_x. To sort industries by how pollution intensive their production technologies are (e.g., Albrizio, Kozluk, and Zipperer (2014); Broner, Bustos, and Carvalho (2016)), we use information on pounds of SO_x emissions per unit of output (SO_x *emission*) in each three-digit SIC industry in the US in 1987 from Levinson (2009). The intersection of the firm-level Compustat data and information on industry-level pollution intensity leaves us with firms in 120 three-digit SIC manufacturing industries.

We list the ten most and least polluting industries (with at least 50 observations) in Panels A and B of Table 3. Hydraulic cement manufacturing (SIC 324) is by far the industry with the highest pollution intensity. The ten most polluting industries emit on average (median) 66.701 (52.898) pounds of SO_x per unit of output compared to 0.067 (0.086) for the ten least polluting industries. Table 2 shows that average (median) SO_x *emission* across all industries is 9.216 (1.086). Thus, the average (median) level of SO_x pollution is more than six (50) times higher in the ten most polluting industries relative to the sample as a whole.

An important benefit of the pollution data from Levinson (2009) is the level of disaggregation. Eight of the top ten most pollution-intensive industries are in three two-digit SIC codes: 28, 32, and 33. Yet, these same broad two-digit categories also contain some of the *least* pollution-intensive industries. For instance, whereas the cement and concrete

[10] The pollution tax changes are staggered across countries, but several of the changes occur in the 1997-2001 period, a time of strong global economic activity. A potential concern is that this strong economic period somehow relaxed constraints for polluting firms *in particular* allowing them to invest more in R&D, thereby generating a spurious association between pollution taxes and firm R&D. We directly confront this potential in Table A.6. In addition, our main cross-industry results are not consistent with this alternative story because the high-pollution industries who respond *most* to pollution taxes are generally among the *least* innovative sectors in the economy. Most notably, the high-tech industries behind the 'R&D boom' of the 1990s (e.g., Brown, Fazzari, and Petersen (2009)) are among the least pollution-intensive sectors in the economy.

industries (SIC 324 and 327) are the most and fourth most SO_x polluting industries, Flat glass (SIC 321), Glass Products, Made Of Purchased Glass (SIC 323), and Cut Stone And Stone Products (SIC 328) are all relatively low polluters (pollute about two pounds per unit of output). SO_x emissions in the Cement industry are around 70 times greater than emissions in these other three industries which are within the same two-digit industry group.

We use pollution intensities from US industries because they are, to the best of our knowledge, the only sufficiently disaggregated and comprehensive measures of cross-industry differences in the emission of major air pollutants (e.g., Lucas, Wheeler, and Hettige (1992)). Another benefit of the pollution intensity data is that it is measured before our sample period begins in a country not included in the sample. However, it is important to note that our identification does not hinge on industry pollution levels being the same across all countries. Rather, the assumption is merely that the relative *ordering* of pollution intensity is similar across countries – e.g., that Cement is generally more pollution intensive (and thereby more heavily treated by higher pollution taxes) than Glass Products. Indeed, we focus primarily on differences across quartiles (or bins) of pollution-intensity, which is even less likely to differ substantially across countries. Consistent with this idea, the evidence in Lucas, Wheeler, and Hettige (1992) and Hettige, Lucas, and Wheeler (1992) suggests that cross-sector differences in pollution are very stable across countries and over time.

The OECD reports relatively disaggregated data on *SO_x emission* for three of our sampled countries: Italy, the Netherlands, and Denmark (see the *Air Emission Accounts*). Table A.2 reports SO_x emission intensity (measured as tonnes of SO_x per million of sales in local currency) for these three countries. The data covers 12 of our sample years (2000-2012) and is reported for 17 two-digit and three-digit ISIC industry classes. Four industries – Coke and refined petroleum products, Other non-metallic mineral products, Basic metals and Chemicals and chemical products – are consistently the most SO_x polluting industries.[11] Notably, these four ISIC industries include nine of the ten most SO_x emitting industries in Table 3. The eighth most SO_x emitting US industry in Table 3, Grain mill products (SIC

[11] Denmark's fourth most polluting industry is instead Food products, beverages and tobacco products. This is because there is essentially no economic activity in Basic metals in Denmark.

204), is part of Food manufacturing, a broadly aggregated sector for the non-US countries in Table A.2. Overall, the comparative evidence in Table A.2 suggests that cross-industry differences in pollution intensity are very similar within the type of developed economy that we study.

3.3.2 Mobility of assets

We also report a proxy for asset mobility in each industry (*Industry immobility*) following Ederington, Levinson, and Minier (2005). This measure captures fixed plant costs of an industry. An industry with higher fixed plant costs is less likely to respond to higher pollution taxes by moving abroad. Notably, as Ederington, Levinson, and Minier (2005) emphasize, the most polluting industries are also the least geographically mobile. In our sample, the correlation between the industry measures of SO_x *emission* and *Industry immobility* is 0.61.

Table A.3 sorts the observations from our full sample into four bins based on SO_x *emission* and *Industry immobility*. We put an observation in the high (low) pollution group if the firm is located in an industry above (below) the median in SO_x *emission*, while simultaneously sorting the observations into immobile (mobile) groups if the firm is in an industry above (below) the median in *Industry immobility*. The largest bin is observations from industries with high pollution intensity and low asset mobility (around 40% of the sample), followed next by industries with low pollution intensity and mobile assets (27% of the sample), high pollution intensity and mobile assets (23% of the sample), and, finally, low pollution intensity and immobile assets (10% of the sample). This sorting shows that while pollution intensity and asset immobility tend to go together, there is still some variation in pollution intensity among firms with immobile production technologies, which we use in some of the empirical tests.

4 Pollution taxes and R&D

4.1 Baseline specification

To evaluate the effects of pollution taxes on firm-level R&D we broadly follow prior work (e.g., Jaffe and Palmer (1997)) and model R&D as a function of output (sales) using the following specification:

$$R\&D_{i,t} = \beta Pollution\ taxes_{c,t-1} + \gamma Sales_{i,t} + \eta_i + \eta_t + \epsilon_{i,t}. \tag{1}$$

In Equation 1, $R\&D_{i,t}$ is the natural logarithm of R&D investment, and *Sales* is the natural logarithm of net sales, in firm *i*, in country *c*, in year *t*. The key explanatory variable is $Pollution\ taxes_{c,t\text{-}1}$, which is the level of SO_x taxation in country *c* at the beginning of year *t*. The specification also includes both firm and year fixed effects (η_i and η_t). The firm fixed effects account for any unobserved, time invariant firm characteristics that may impact R&D, including any stable characteristics of the country in which the firm operates (e.g., culture, institutional quality, etc.). The year fixed effects control for aggregate time-varying shocks common to all firms in all countries.

We also estimate augmented versions of Equation 1 where we focus on differences in the within-firm response to $Pollution\ taxes_{c,t\text{-}1}$ across industries with differing exposure to the tax. To implement these difference-in-differences tests, we sort firms into quartiles based on the SO_x emission intensity for the industry in which the firm is located (Q_k *of* SO_x *polluters*). We then interact this pollution intensity indicator with the time-varying measure of country *Pollution taxes*.[12] If *Pollution taxes* have a causal impact on technology adoption at the firm-level, the effects *should be* relatively stronger in firms who are more exposed to (or treated by) the tax. In these specifications we can include country-year fixed effects ($\eta_{c,t}$), which broadly account for any time varying country-level factors that affect R&D investment across all firms (such as changes in a given country's economic opportunities or

[12] Our inferences are similar if use the direct (continuous) measure of SO_x emission intensity rather than the separate quartiles. A key advantage of using the quartile approach is that while a given industry's actual emission intensity may change over time (and across countries), industries are much less likely to move into different quartile bins, as cross-industry differences in *relative* pollution intensity are very stable over time.

R&D incentive policies).

4.2 Baseline results

Columns 1-2 in Table 4 report estimates of Equation 1. The β coefficient reported in column 1 is positive and highly statistically significant, showing that increases in country-level pollution tax rates are associated with more firm-level R&D spending. The estimate (0.068) suggests that a one standard deviation increase in *Pollution taxes* is, on average, associated with an increase in firm R&D of around 0.13, or approximately 12% of the sample average *R&D*. Column 2 shows that the estimate on the *Pollution taxes* term is almost identical if we control for a standard set of time-varying firm-level characteristics (*Cash flow-to-assets*$_t$, *Sales growth*$_t$, *Cash holdings*$_{t-1}$, and *Total debt-to-assets*$_{t-1}$). Given that including these variables has no impact on our inferences, we focus on the baseline specification in the remainder of the study.

In column 3 we explore whether the estimated effects of pollution taxes show up before the tax is introduced. Clearly, if the relationship between pollution taxes and R&D is causal, R&D should not respond until *after* pollution taxes are first put in place. We thus replace the continuous measure of *Pollution taxes* with three dummy variables: i) *Pollution taxes*$^{(t-1,\ t-2)}$, which equals one in each of the two years immediately preceding the first introduction of a pollution tax and zero otherwise, ii) *Pollution taxes*$^{(t,\ t+1)}$, which equals one in the first two years a pollution tax is in place, and iii) *Pollution taxes*$^{(\geq\ t+2)}$, which equals one for two or more years after the tax is in place. Notably, the coefficient estimate on *Pollution taxes*$^{(t-1,\ t-2)}$ is near zero and statistically insignificant, suggesting that R&D is not already trending higher prior to the first introduction of a pollution tax. On the other hand, the coefficient on *Pollution taxes*$^{(\geq\ t+2)}$ term is much larger in magnitude and statistically significant, showing that the effects of pollution tax changes are entirely concentrated in the years after the tax is first implemented.

In the remainder of Table 4 we report the same set of regressions with *Fixed assets* rather than *R&D* as the dependent variable.[13] In sharp contrast to the findings for R&D, *Pollution*

[13] All results are similar if we focus on the flow of new capital spending rather than the stock of fixed assets.

taxes are, if anything, negatively related to *Fixed assets*, although the negative coefficient estimates are not statistically significant at conventional levels. These results are valuable because they show that *Pollution taxes* are not broadly related to the expansion of all types of firm assets, perhaps for spurious reasons. Similarly, this evidence mitigates concerns about omitted variables because most such factors (e.g., investment opportunities) would have similar effects on both *R&D* and fixed capital accumulation. Finally, to the extent that a firm's stock of fixed assets reflects its reliance on older, dirtier production technologies, a positive association between *Pollution taxes* and *Fixed assets* would be inconsistent with higher pollution taxes inducing (clean) technical change.

4.3 Industry characteristics

4.3.1 Pollution intensity

Table 5 reports estimates of Equation 1 augmented with interactions between country *Pollution taxes* and the indicators of industry pollution intensity (based on SO_x *emission*, as explained above). We estimate the augmented regressions for both *R&D* (columns 1-3) and *Fixed assets* (columns 4-6). We start with a specification that includes aggregate year fixed effects (as in Equation 1), then estimate specifications with country-year and industry-year fixed effects. The country-year fixed effects absorb the uninteracted *Pollution taxes* term, isolating the within-country, across-industry effects of changes in *Pollution taxes* on firm R&D.

The estimates in columns 1-3 show that changes in *Pollution taxes* share a differentially stronger positive relation with *R&D* in the most pollution-intensive industries. For example, in column 3 the coefficients on the *Pollution taxes* x Q_k *of* SO_x *polluters* interactions are positive and statistically signficant for the two most pollution-intensive quartiles. These coefficients are around 0.07, indicating that, for every one standard deviation increase in *Pollution taxes*, firms located in industries with above-median pollution intensity increase *R&D* by approximately 0.133 *more than* firms in industries with the lowest pollution intensity. This differential effect is around 13% of the sample average level of *R&D*.

In contrast, columns 3-6 in Table 5 show no differential relation between *Pollution taxes* and firm *Fixed assets*. In fact, the coefficient estimates are consistently negative, though only in one case is the negative coefficient statistically significant. Overall, these results are consistent with the firms most treated by pollution taxes disproportionately increasing their technological absorptive capacity.

One potential concern with the results in Table 5 is that a country's pollution tax rate is correlated with some other country characteristic, and that it is actually this alternative characteristic that drives the positive (differential) association between pollution taxes and R&D. We consider the following three characteristics that vary by country and year and at least have the potential to be positively correlated with pollution taxes *and* disproportionately important for R&D in high pollution industries: i) the level of economic development, as measured by GDP per capita (*Development*), ii) the level of public funding for environmental innovation, measured by public sector spending on environmental R&D (*Env. R&D*), and iii) the user cost of R&D (*User cost*), which captures any changes in a country's R&D tax credits.[14] We estimate the augmented version of Equation 1 with each of these different country characteristics interacted with the pollution intensity quartiles (Q_k *of* SO_x *polluters*). Figure 2 shows how the coefficient on the interaction between pollution taxes and Q_4 *of* SO_x *polluters* changes when these additional interactions are included in the regression. The results show that regardless whether we include the interactions with the other country characteristics one by one or all together, the coefficient on the *Pollution taxes* x Q_4 *of* SO_x *polluters* is very similar in sign and significance to the estimates in Table 5.

4.3.2 Industry immobility

Next we consider whether the differential effects we document in Table 5 are affected by the mobility of the industry's assets. The expectation is that these differential effects are driven primarily by firms operating in industries with more immobile assets, as these firms cannot readily relocate production to avoid higher pollution taxes. Put another way, firms

[14] These three country characteristics are unrelated to pollution taxes. The correlation between *Pollution taxes* and *Development*, *Env. R&D*, and *User cost* is -0.303, -0.001, and 0.123, respectively.

with more mobile assets might respond to pollution taxes by relocating their existing assets rather than investing in R&D to expand their absorptive capacity.

Table 6 reports separate estimates of the differential specification for industries sorted by the *Industry immobility* measure. Column 1 shows that among industries with above median *Industry immobility*, there is a strong differential association between *Pollution taxes* and *R&D* in more pollution-intensive industries. The coefficient on the interaction between pollution taxes and the indicator variable for the top 25% highest pollution industries is twice as large as in the corresponding regression reported in column 1 in Table 5. On the other hand, among the firms located in industries with more mobile assets (below median *Industry immobility*) we find no systematic evidence of a positive association between pollution taxes and R&D investment across more pollution-intensive industries.

Columns 3 and 4 report corresponding estimates with *Fixed assets* as the dependent variable. Among firms in less mobile industries (column 3), there is no relation between pollution taxes and fixed assets. Interestingly, however, for firms with more mobile assets (column 4) there is a consistently *negative* relation between pollution taxes and fixed assets in more treated (pollution intensive) industries. Notably, for firms with relatively low relocation costs and relatively high pollution intensity, there is a statistically significant negative association between pollution taxes and fixed assets.

The full set of results in Table 6 is consistent with the idea that firms respond to higher taxes on dirty production technologies by increasing their capacity to absorb new technology if their production relies on relatively immobile assets, while those firms with more mobile assets respond to the higher pollution tax by reducing their stock of fixed assets rather than innovating. This evidence is valuable for multiple reasons. On the one hand, these results are plausible, both in terms of showing the interesting heterogeneities that exist across fixed assets and R&D, and by documenting relatively stronger effects in areas where the effects *should be* stronger. In this way, the results support the validity of our estimation approach. In addition, these results highlight the fact that environmental policy can have sharply different effects on different types of firms and industries, which is important for adequately evaluating the aggregate consequences of policy change. We explore more of these heterogeneous effects below.

4.4 Robustness checks

We report numerous robustness checks in Table A.4-Table A.7 in the appendix. Table A.4 shows that our findings are not driven only by a particular country (or set of countries). Panel A of Table A.4 reports estimates of the baseline specification, while Panel B reports estimates of the main regression augmented with interactions between *Pollution taxes* and the pollution intensity quartiles (Q_k *of* SO_x *polluters*). In columns 1-4 we show that excluding the three countries which contribute the most observations to our sample (Canada, Japan, and the UK) has no impact on our inferences, whether we drop the countries one-by-one, or all of them simultaneously. Perhaps most notably, despite the sharp decline in sample size (from 36,449 to 10,347 observations) that occurs when we drop all three of the largest countries, we continue to find a positive and significant differential effect of higher pollution taxes on R&D in the most pollution-intensive industries. Column 5 shows that we also find similar results if we drop the countries that contribute very few firms (Austria, Greece, Ireland, Korea and Spain) to the sample, and column 6 shows that excluding countries with no variation in SO_x taxation has very little impact on our estimates.

Table Table A.5 shows that our findings are robust to using alternative dependent variables. In columns 1-2 we normalize R&D by scaling by lagged total assets and continue to find a positive and signficant effect among firms in the most treated (highest pollution) industries. In columns 3-4 we focus on capital spending as the dependent variable rather than the stock of fixed assets. The results show that, unlike for R&D, firms more heavily treated by higher pollution taxes do not increase investment in new fixed capital.

The results in Table A.6 address the fact that cross-country changes in *Pollution taxes* tend to be concentrated in the late 1990s and early 2000s, raising the potential concern that some common omitted economic shock is behind our findings. It is important to emphasize that, given our identification approach, for such an omitted factor to explain our results it must not only be correlated with the implementation of higher pollution taxes, but also differentially important for R&D in the most pollution-intensive industries (industries which are generally the *least* innovative). Nonetheless, we address this concern in Table A.6 by including interactions between the industry pollution intensity indicators and a dummy variable taking on the value one in 1997-2001, the years where pollution tax increases are most common in our sample. The results in columns 1 and 2 show that there is no systematic relation between the 1997-2001 time period and R&D investment in more pollution intensive industries. That is, irrespective of pollution taxes, more pollution intensive industries were not becoming more R&D intensive in the 1997-2001 period. Moreover, columns 3-4 show that including the additional interactions alongside the main *Pollution taxes* x Q_k *of* SO_x *polluters* terms has no impact on our inferences.

In Table A.7 we address potential concerns about time-series changes in industry growth opportunities by controlling for time-series changes in the industry's share of total R&D and total employment in the country. Perhaps countries systematically introduce higher pollution taxes at precisely the time that the high-pollution industries located in the country encounter more innovation opportunities or growth prospects. Again, for this story to work, countries would have to systematically (and correctly) *anticipate* the arrival of these options, as Table 4 shows that R&D does not change until well after pollution taxes are increased. The evidence in Table A.7 shows that while both of these industry share measures are positively associated with R&D (and significantly so in the case of industry share of employment), adding them as controls has little impact on our estimates, particularly our finding of a relatively stronger linkage between pollution taxes and R&D in the most pollution-intensive industries.

5 Does access to finance affect the R&D response to pollution taxation?

Here we consider how access to finance influences the way firms respond to pollution taxes. Several studies conclude that R&D is sensitive to the availability of internal and external finance; notably, better access to market-based financing sources (e.g., public equity and debt markets) appears to be particularly important for the extent to which smaller and younger firms can invest in R&D (e.g., Brown, Fazzari, and Petersen (2009); Brown, Martinsson, and Petersen (2012)). This evidence suggests that some firms may be better positioned than others to respond to pollution taxes by expanding their absorptive capacity.

5.1 Sorts based on indicators of financing constraints

In Table 7 we augment the baseline Equation 1 with an interaction between the country-level *Pollution taxes* measure and alternative indicators of the likelihood a firm is financially constrained. We start in columns 1 and 2 with sorts based on firm size. In column 1 we interact *Pollution taxes* with the firm's average *Firm size* over the sample period (based on the book value of total assets), and in column 2 we interact *Pollution taxes* with *Large firm*, an indicator variable equal to one for all firms above the industry median in *Firm size*. In either case, the interaction term is positive and significant, showing that when pollution taxes increase, large firms increase R&D more than small firms do. Indeed, the estimates on the uninteracted *Pollution taxes* term in column 2 show that among the smallest 50% of firms in a given industry, there is no meaningful R&D response to an increase in pollution taxes.

In the final two columns of Table 7 we sort firms using two commonly used measures of financing constraints: *Size-age index* (Hadlock and Pierce (2010)) and *Whited-Wu index* (Whited and Wu (2006)). Both measures use a vector of firm characteristics to construct an index that reflects financing constraints, with a higher value suggesting a firm is more financially constrained (Table 1 provides details on index construction). In column 5, the interaction between *Pollution Taxes* and the *Size-age index* is negative and statistically significant, indicating that more financially constrained firms invest relatively less in R&D when pollution taxes increase. The estimates using the *Whited-Wu index* in column 6 also support the idea that financing constraints limit a firm's ability to respond to pollution taxes by expanding absorptive capacity.

5.2 Access to external finance and the R&D response to pollution taxation

Here we explore the linkages between finance and the R&D response to pollution taxes in more detail. To do this we build two measures of the revealed access a firm has to external finance: *Market based finance* and *Bank based finance*. *Market based finance* is an indicator variable equal to one if a firm has issued new debt or equity at some point in the sample period, while *Bank based finance* is an indicator variable equal to one if *Market based finance* is zero but the firm has leverage of at least 10% relative to the book value of total assets.

Table 8 reports estimates of Equation 1 augmented with the interaction between *Pollution taxes* and one (or both) of the external finance indicators. We report full sample estimates, as well as separate estimates for large and small firms, using the same approach for sorting on firm size that we used in Table 7.[15] Column 1 shows that, for the full sample, the coefficient on the interaction between *Market based finance* and *Pollution taxes* is positive but statistically insignificant, while the coefficient on the uninteracted *Pollution taxes* term is positive and statistically significant, similar to the results in Table 4. For the sub-set of large firms (column 2), the coefficient on the uninteracted *Pollution taxes* measure is larger in magnitude compared to the full sample result and highly significant, but the coefficient on the interaction with *Market based finance* term is essentially zero, indicating that the availability of external finance has no impact on how large firms respond to changes in pollution tax rates. For the sub-set of small firms (column 3), on the other hand, it is the coefficient on the uninteracted *Pollution taxes* term that is close to zero, while the coefficient on the *Pollution taxes* x *Market based finance* interaction is positive, large in magnitude, and statistically significant. Thus, the availability of market based financing has an important impact on whether or not small firms respond to higher pollution taxes by increasing R&D. Indeed, for small firms without access to market based financing there is no R&D response whatsoever (on average) to an increase in pollution taxes, consistent with the relatively stronger overall response we document among large firms in Table 7.

In columns 4-6 we repeat these tests using access to bank financing (*Bank based finance*) rather than *Market based finance*. The general pattern of results is similar for the bank based measure, though the magnitudes are smaller, suggesting that access to arm's-length financing has a more important impact than bank financing on the way small firms respond

[15] Table A.8 shows that our inferences are similar if we use the other financing constraint sorts reported in Table 7.

to higher pollution taxes. We draw similar conclusions from the results in columns 7-9, which simultaneously include the *Pollution taxes* x *Market based finance* and *Pollution taxes* x *Bank based finance* interactions.

The results in Table 8 are noteworthy for several reasons. First, they support the idea that access to finance influences how firms respond to an increase in pollution taxes. Together with the evidence in Table 7, we find strong and consistent evidence that firms who appear to face binding financing constraints and do not have access to market based financing do not increase their absorptive capacity in the face of higher pollution taxes. Second, these findings highlight important heterogeneities across firms that other studies on environmental policy and innovation would miss, particularly studies using industry or country level data. Third, these findings suggest that the effectiveness of environmental taxes at inducing clean technology adoption will depend, at least to some extent, on the institutional environment in which the taxes are introduced. For example, our results suggest that higher taxes on polluting activities will induce much broader technology adoption in countries with more developed capital markets. As far as we know, the literature on directed technical change has largely (if not entirely) ignored the potential for such important differences in the effects of environmental taxes across firms and countries.

6 Aggregate effects

To the extent that firms invest in R&D to increase their ability to absorb new technologies (e.g., Cohen and Levinthal (1989); Griffith, Redding, and Van Reenen (2003)), our findings highlight a novel micro-level mechanism through which pollution taxation can influence the nature and direction of technical change. An open question, however, is whether the micro-level adjustments we focus on also show up in more aggregated measures of innovative activity. This question is particularly intriguing given the heterogeneous effects we document across different types of firms: Is the R&D response among financially unconstrained firms sufficient to affect industry levels of R&D investment and the country production of new air pollution abatement technologies?

6.1 R&D at the industry level

We use the firm-level data to build a country-industry-year panel and estimate the following regression:

$$Industry\ R\&D_{cj,t} = \delta(Pollution\ Taxes_{c,t-1}) + \lambda Industry\ Sales_{cj,t} + \eta_{cj} + \eta_t + \epsilon_{cj,t}. \quad (2)$$

In Equation 2, $Industry\ R\&D_{cj,t}$ is the log of the sum of total R&D ($\sum R\&D_{cj,t}$) and $Industry\ Sales_{cj,t}$ is the log of the sum of total sales ($\sum Sales_{cj,t}$) in country-industry cj in year t. Equation 2 also includes country-industry (η_{cj}) and year (η_t) fixed effects. The country-industry fixed effects account for any unobserved, time invariant characteristics that affect R&D investment in an industry in a given country, while the year fixed effects control for aggregate time-varying shocks common to all countries.[16]

Column 1 in Table 9 shows that there is a positive association between country pollution taxes and industry levels of R&D, consistent with the baseline firm-level estimates in Table 4. More importantly, in column 2 we add interactions between country *Pollution taxes* and the indicator variables reflecting industry pollution intensity. The coefficient estimates increase across the three interaction terms, but only the coefficient on the interaction with the fourth quartile of pollution intensity is positive and significant. Column 3 shows that the estimates are similar if we replace the year fixed effects with country-year fixed effects. Overall, the industry-level results are consistent with the strong differential effects we documented in the firm-level analysis.

6.2 The country stock of air pollution abatement technologies

If firms invest in R&D in order to expand their capacity to absorb and adopt more efficient pollution abatement technologies, the aggregate demand for such technologies should increase. However, as discussed above, it is typically not the polluting firms themselves

[16]Our focus in this section on industry-level R&D expenditures is consistent with the main outcome measure in Jaffe and Palmer (1997), though they focus on a much different environmental policy (regulatory compliance costs) and sample (US industries). One advantage of our sample is the ability to estimate difference-in-differences across industries more or less exposed to pollution taxation.

who invent new and cleaner production technologies, though at times they collaborate with others (e.g., De Marchi (2012); Frey, Iraldo, and Testa (2013)). Thus, the relevant unit of analysis for evaluating how pollution taxes affect new innovations in clean technology is, *at a minimum*, the country level (the market for new environmentally sustainable technologies has been to shown to be unusually international in scope (e.g., Lanjouw and Mody (1996); Söderholm and Klaasen (2007))). Admittedly, it is harder to establish causality with the country-level analysis, but we can at least explore whether the country-level evidence is consistent with the micro-level mechanism we have emphasized.

We estimate the following regression

$$Patent\ count_{c,t} = \alpha_1(Pollution\ Taxes_{c,t-1}) + \alpha_2 K_{air,ct-1} + \alpha_3 K_{noair,ct-1} + \eta_c + \eta_t + \epsilon_{c,t}, \quad (3)$$

where $Patent\ count_{c,t}$ is either the natural logarithm of the stock of triadic patents classified in air pollution abatement technologies, or the stock of all non-air pollution abatement technologies by country c in year t.[17] We construct patent stocks by country for both air pollution abatement technologies ($K_{air,ct\text{-}1}$) and all non-air pollution abatement technologies ($K_{noair,ct\text{-}1}$).[18] We also include $\mathbf{X}_{\mathrm{c,t}}$, which is a vector of time-varying country control variables, including *Public environmental R&D-to-GDP* and *GDP per capita*. Equation 3 also includes country fixed effects (η_c) and year fixed effects (η_t).

Table 10 reports estimates of Equation 3. The results in columns 1-3 show a statistically significant positive association between *Pollution taxes* and patents in air pollution abatement technologies. There is also a strong and positive effect from the country's stock of past inventions in air pollution abatement technologies on current patent counts, which is plausible. The country's stock of non-air pollution abatement technologies, on the other hand, is not robustly related to new inventions in air pollution abatement.

[17] We follow the OECD's patent strategies for identification of air pollution abatement technologies (ENV-TECH). We focus on triadic patents as they are are typically considered to capture the most valuable inventions (see e.g., Aghion, Dechezleprêtre, Hemous, Martin, and Van Reenen (2016)).

[18] We begin in 1985, which is the first year that OECD presents patent data for air pollution abatement technologies, and apply the perpetual inventory method and assume a deprecation rate of 20% (as in Aghion, Dechezleprêtre, Hemous, Martin, and Van Reenen (2016)). We do the same for both the patent stock of air pollution abatement technologies and non-air pollution abatement technologies. Both patent stocks are in logs.

Public environmental R&D is also positively related to air pollution abatement patents, but controlling for these public investments only strengthens the association between pollution taxes and air pollution abatement patents.

One concern with these results is that countries increase pollution taxes when, for some omitted reason, they are becoming more broadly innovative. We therefore estimate Equation 3 with the stock of all triadic patents that are *not* classified as air pollution abatement technologies and report the results in columns 4-6. The estimate on *Pollution taxes* is near zero and never statistically significant when the stock of non-air pollution inventions is the outcome variable. Further, as expected, the stock of past inventions in air pollution abatement is not related to patenting in non-air pollution abatement technologies. On the other hand, the stock of all non-air pollution abatement patents has a highly significant and positive relationship with current invention rates of non-air pollution technologies.

7 Conclusions

We find that higher taxes on air pollution are associated with a substantial within-firm increase in R&D spending. Pollution taxes have relatively stronger effects on R&D in sectors with dirtier production technologies and relatively immobile assets, as expected if the relation between pollution taxes and R&D is causal. Given the key role R&D plays in the firm's ability to implement and adopt new technologies (e.g., Griffith, Redding, and Van Reenen (2004)), our study provides direct evidence of a micro-level mechanism through which environmental taxes can affect technical change.

This evidence is particularly relevant for the theoretical literature on environmental policy and directed technical change (e.g., Acemoglu, Akcigit, Hanley, and Kerr (2016)). While our evidence broadly supports the central mechanism emphasized in this literature, we also show that access to finance plays a key role in determining how firms respond to pollution tax increases. As such, our work suggests that financing considerations should figure more prominently in future efforts to understand and model the process of directed technical change.

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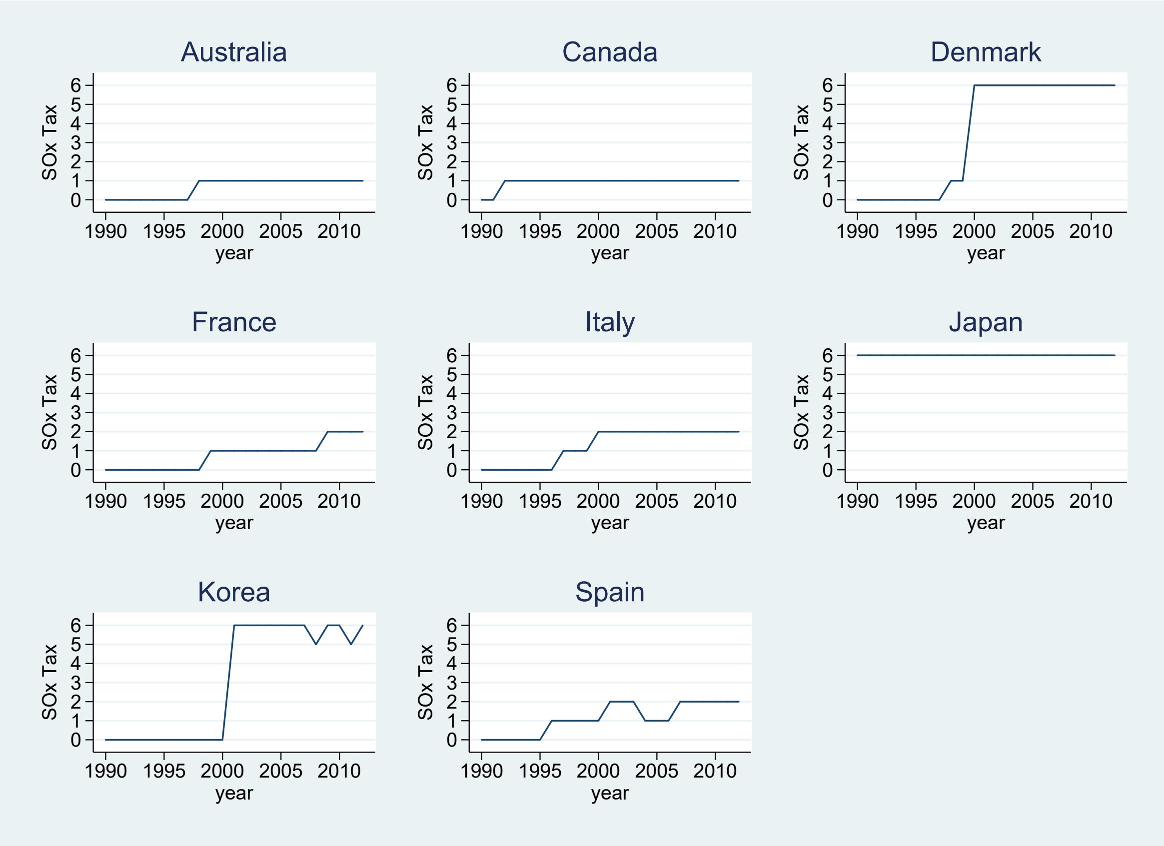

Figure 1: SO_x taxation, 1990-2012

Figure 1 reports the the evolution of Sulphur oxides (SO_x) taxation by country and over time. Our sample consists of 10 countries which does not have a SO_x tax: Austria, Belgium, Finland, Germany, Greece, Ireland, Netherlands, Norway, Sweden and the UK. Source: OECD.

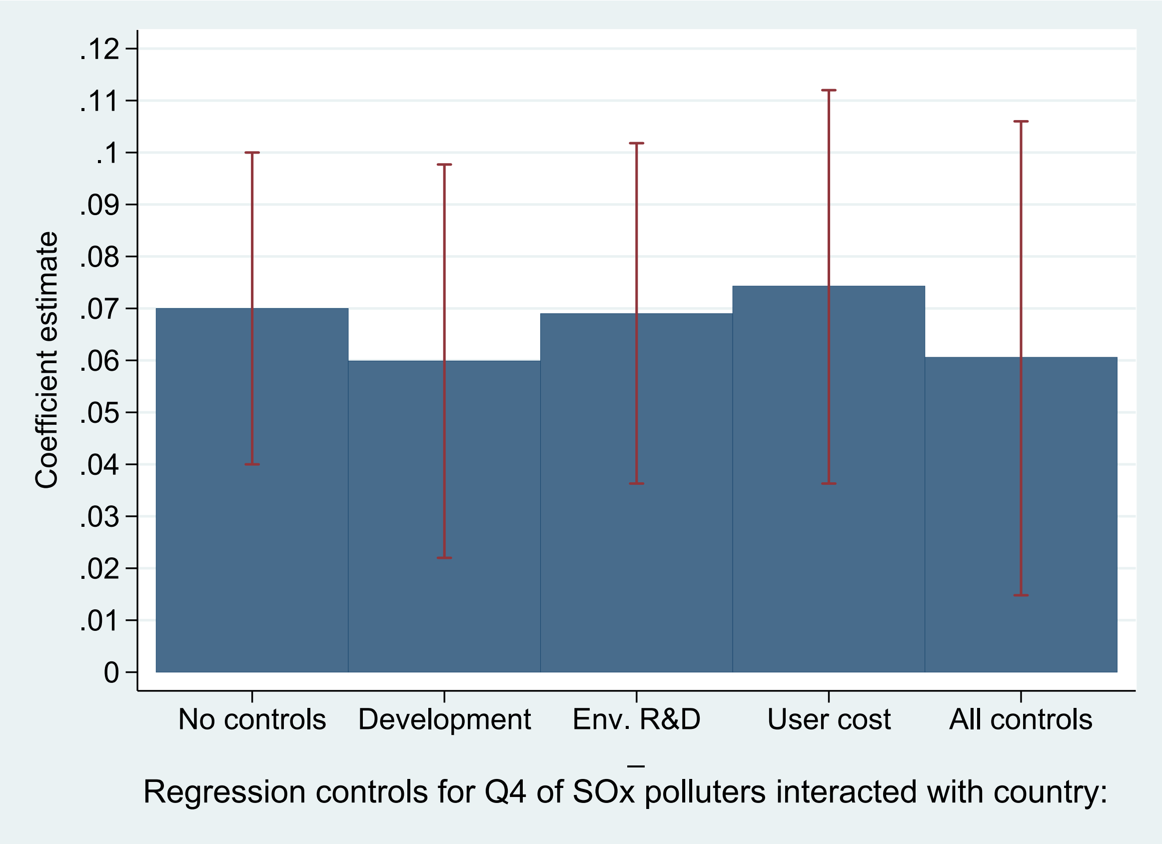

Figure 2: Robustness of the estimated relation between pollution taxes and R&D to alternative country-level mechanisms

Figure 2 summarizes how adding a series of alternative country-level control variables to the augmented version of Equation 1 affects the coefficient on *Pollution taxes* x Q_4 *of* SO_x *polluters* with *R&D* as dependent variable. The additional country-level variables are: GDP per capita (*Development*), public environmental R&D to GDP (*Env. R&D*), the user cost of R&D (*User cost*). The additional country-level variables are interacted with Q_k *of* SO_x *polluters* and added to the regression alongside the firm and country-year fixed effects. Table 1 provides detailed variable definitions. The standard errors are clustered at the country level. The columns in the figure indicate the coefficient estimate on *Pollution taxes* x Q_4 *of* SO_x *polluters*, while the bands represent 95% confidence intervals.

Table 1: Description of variables

Variable name	Definition	Source
R&D	The natural logarithm of firm level research and development (R&D) expenditures and Winsorized at the 1% level.	Compustat Global
Fixed assets	The natural logarithm of firm level book value of plant, property and equipment and Winsorized at the 1% level.	Compustat Global
Sales	The natural logarithm of firm level sales and Winsorized at the 1% level.	Compustat Global
Cash flow-to-assets	Cash flow divided by the beginning of year book value of total assets and Winsorized at the 1% level.	Compustat Global
Sales growth	First difference in the natural logarithm of firm level sales and Winsorized at the 1% level.	Compustat Global
Cash holdings	The natural logarithm of firm level cash holdings and Winsorized at the 1% level.	Compustat Global
Total debt-to-assets	Total debt divided by book value of total assets and Winsorized at the 1% level.	Compustat Global
Firm size	The natural logarithm of firm book value of total assets, averaged over the sample period, relative to the firm with with largest (average) book value of total assets in the industry.	Compustat Global
Large firm	An indicator variable taking on the value one (zero) if the firm is above (below) the median in *Firm size*.	Compustat Global
Size-Age index	Computed as in Hadlock and Pierce (2010): -0.737*(Natural logarithm of book value of total assets) + 0.043*(Natural logarithm of book value of total assets)^2 - 0.04*(Natural logarithm of one plus number of years since first appearing in Compustat), and Winsorized at the 1% level.	Compustat Global

Whited-Wu index	Computed as in Whited and Wu (2006): -0.091*(cash flow divided by book value of total assets) - 0.062*(An indicator variable taking on the value one if the firm pays dividend) + 0.021*(long term debt divided by book value of total assets) - 0.044*(natural logarithm of book value of total assets) + 0.102*(First difference in (industry) natural logarithm of sales) - 0.035*(First difference in (firm) natural logarithm of sales), and Winsorized at the 1% level.	Compustat Global
Market based finance	An indicator variable taking on the value one if the firm has issued debt or equity sometime during the sample period or zero otherwise.	Compustat Global
Bank based finance	An indicator variable taking on the value one if the firm has an average long term debt-to-assets ratio of at least 0.10 over the sample period and zero in *Market based finance* or zero otherwise.	Compustat Global
Pollution taxes	Taxes and charges directly applied to the pollution of sulfur oxides (SO_x). It is based on the tax rate in Euros per tonne pollution by country and year. Categorized between 0 to 6 indicating low to high taxation level.	Botta and Kozluk (2014)
SO_x emission	Pounds of sulfur oxides (SO_x) per unit of output in each three digit SIC industry in the US manufacturing sector in 1987.	Levinson (2009)
Industry immobility	The ratio of real structures capital stock to the total value of shipments in each three digit SIC industry in the US manufacturing averaged over the 1980s.	Bartelsman and Gray (1996) and Becker, Gray, and Mavakov (2016)

Table 2: Summary statistics

Table 2 reports summary statistics for the key variables included in this study. Table 1 provides detailed variable definitions.

	Obs	Mean	Median	SD
R&D	36,904	1.024	0.326	1.413
Fixed assets	36,902	4.262	4.352	2.197
Sales	36,421	2.778	2.326	2.721
Cash flow-to-assets	36,904	0.066	0.082	0.171
Sales growth	36,229	0.043	0.035	0.313
Cash holdings	36,605	0.885	0.578	2.526
Total debt-to-assets	36,897	0.218	0.187	0.194
Firm size	36,904	0.601	0.608	0.215
Large firm	36,904	0.499	0.000	0.500
Size-Age index	36,904	-0.450	-0.458	0.150
Whited-Wu index	36,737	-0.291	-0.302	0.114
Market based finance	36,904	0.330	0.200	0.329
Bank based finance	36,904	0.315	0.000	0.464
Pollution taxes	414	0.959	0.000	1.898
SO_x *emission*	120	9.216	1.086	21.603
Industry immobility	120	0.230	0.206	0.110

Table 3: Pollution intensity and R&D investment in selected industries

Table 3 lists the 10 most (panel A) and 10 least polluting (panel B) industries (with more than 50 observations). *SO_x emission* measures the total amount of pollution (in terms of pounds) of sulfur oxides (SO_x) per unit of output in the US based on data from Levinson (2009). *Industry immobility* measures the fraction of fixed plant equipment relative to shipments measured as in Ederington, Levinson, and Minier (2005) and based on data from Bartelsman and Gray (1996) and Becker, Gray, and Mavakov (2016). *R&D* is average R&D (in logs) per industry. Table 1 provides detailed variable definitions.

SIC	Industry	SO_x emission	Industry immobility	R&D	# obs.
	Panel A: 10 most polluting industries				
324	Cement, Hydraulic	140.330	0.766	0.958	108
299	Misc. products of petroleum and coal	119.471	0.114	1.274	75
281	Industrial inorganic chemicals	82.974	0.329	0.702	493
327	Concrete, gypsum and plaster products	71.692	0.285	0.513	335
331	Steel works, blast furnaces, mills	53.392	0.440	0.712	894
333	Primary smelting and refining	52.404	0.380	0.794	317
329	Abrasive, asbestos and misc.	42.567	0.324	0.784	328
204	Grain mill products	36.625	0.155	0.419	292
287	Agricultural chemicals	34.352	0.302	0.756	317
286	Industrial organic chemicals	32.929	0.376	0.644	343
	Mean 10 most polluting	66.701	0.347	0.756	350
	Median 10 most polluting	52.898	0.326	0.734	323
	Panel B: 10 least polluting industries				
382	Laboratory apparatus and instruments	0.141	0.205	0.903	1,409
275	Commercial printing	0.112	0.153	0.855	210
341	Metal cans and shipping containers	0.112	0.140	1.017	116
355	Special industry machinery, ex. metal	0.090	0.240	0.873	1,510
384	Photographic, medical and optical goods	0.087	0.154	1.077	1,665
357	Computer and office equipment	0.085	0.185	1.028	1,162
205	Bakery products	0.024	0.220	0.164	152
394	Dolls, toys, games and sporting	0.009	0.211	0.760	416
365	Household audio and video equipment	0.006	0.174	1.210	352
345	Screw machine products, bolts, nuts, etc	0.001	0.259	0.265	141
	Mean 10 least polluting	0.067	0.194	0.815	713
	Median 10 least polluting	0.086	0.195	0.864	384

Table 4: Pollution taxes and firm investment

Table 4 reports OLS estimates of Equation 1 with *R&D* as the dependent variable in columns 1-4 and *Fixed assets* in columns 5-8. All regressions include firm and year fixed effects. Economic effect is one standard deviation in *Pollution taxes* multiplied with the estimated baseline coefficient for *Pollution taxes* (top row in results table). % of mean is the economic effect divided by the sample average *R&D* (*Fixed assets*) in columns 1-4 (5-8). Average *R&D* (*Fixed assets*) is 1.024 (4.262). Columns 2 and 6 include the following firm level control variables: *Cash flow-to-assets*$_t$, *Sales growth*$_t$, *Cash holdings*$_{t-1}$, and *Total debt-to-assets*$_{t-1}$. Table 1 provides detailed variable definitions. The standard errors are clustered at the country level. ***, **, and * stand for significance at the 1%, 5%, and 10% levels.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	R&D				*Fixed assets*			
Pollution taxes$_{c,t-1}$	0.068	0.065	0.068		-0.018	-0.023	-0.015	
	(0.016)***	(0.016)***	(0.016)***		(0.029)	(0.037)	(0.027)	
Sales$_{i,t}$	0.287	0.294	0.287	0.288	0.313	0.307	0.313	0.313
	(0.034)***	(0.035)***	(0.034)***	(0.033)***	(0.035)***	(0.041)***	(0.035)***	(0.035)***
Pollution taxes$^{(t-1,\ t-2)}$			0.006	0.016			0.056	0.028
			(0.126)	(0.100)			(0.070)	(0.094)
Pollution taxes$^{(t,\ t+1)}$				0.029				-0.105
				(0.043)				(0.086)
Pollution taxes$^{(\geq\ t+2)}$				0.064				-0.026
				(0.019)***				(0.032)
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm control set	No	Yes	No	No	No	Yes	No	No
Observations	36,449	34,045	36,449	36,449	36,419	34,044	36,419	36,419
R^2	0.467	0.566	0.466	0.471	0.232	0.213	0.237	0.218
Economic effect	0.129	0.123			-0.034	-0.044		
% of mean	12.60	12.05			-0.80	-1.02		

Table 5: Pollution taxes and firm investment: Pollution intensity

Table 5 reports OLS estimates of Equation 1 with *R&D* as the dependent variable in columns 1-3 and *Fixed assets* in columns 4-6. All regressions include firm fixed effects, columns 1 and 3 (2-3 and 5-6) include year (country-year) fixed effects and columns 3 and 6 include industry-year fixed effects. Q_k *of* SO_x *polluters* is an indicator variable taking on the value one if the firm is located in the k^{th} quartile in SO_x *emission*. Table 1 provides detailed variable definitions. The standard errors are clustered at the country level. ***, **, and * stand for significance at the 1%, 5%, and 10% levels.

	(1)	(2)	(3)	(4)	(5)	(6)
		R&D			*Fixed assets*	
Pollution taxes$_{c,t\text{-}1}$	0.029			0.035		
	(0.013)**			(0.043)		
Sales$_{i,t}$	0.287	0.244	0.238	0.313	0.361	0.351
	(0.034)***	(0.029)***	(0.028)***	(0.035)***	(0.030)***	(0.034)***
Pollution taxes$_{c,t\text{-}1}$ *x*	0.029	0.027	0.005	-0.154	-0.142	-0.143
Q_2 *of* SO_x *polluters*	(0.024)	(0.014)*	(0.031)	(0.116)	(0.132)	(0.097)
Pollution taxes$_{c,t\text{-}1}$ *x*	0.059	0.058	0.077	-0.090	-0.054	-0.060
Q_3 *of* SO_x *polluters*	(0.044)	(0.023)**	(0.031)**	(0.033)**	(0.052)	(0.038)
Pollution taxes$_{c,t\text{-}1}$ *x*	0.068	0.070	0.061	-0.053	-0.026	-0.028
Q_4 *of* SO_x *polluters*	(0.016)***	(0.014)***	(0.020)***	(0.038)	(0.039)	(0.033)
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	No	No	Yes	No	No
Country-year fixed effects	No	Yes	Yes	No	Yes	Yes
Industry-year fixed effects	No	No	Yes	No	No	Yes
Observations	36,449	36,449	36,449	36,419	36,419	36,419
R^2	0.437	0.462	0.447	0.237	0.219	0.123

Table 6: Pollution taxes and firm investment: Pollution intensity and industry immobility

Table 6 reports OLS estimates of Equation 1 with *R&D* as the dependent variable in columns 1-2 and *Fixed assets* in columns 3-4. *Q_k of SO_x polluters* is an indicator variable taking on the value one if the firm is located in the k^{th} quartile in *SO_x emission*. *Immobile industry* is an indicator variable taking on the value one (zero) if the industry is above (below) the median in *Industry immobility*. Table 1 provides detailed variable definitions. The standard errors are clustered at the country level. ***, **, and * stand for significance at the 1%, 5%, and 10% levels.

	(1)	(2)	(3)	(4)
	Immobile industry			
	Yes	*No*	*Yes*	*No*
	R&D		*Fixed assets*	
Pollution taxes$_{c,t\text{-}1}$	-0.011	0.030	0.011	0.036
	(0.035)**	(0.015)*	(0.042)	(0.052)
Sales$_{i,t}$	0.261	0.321	0.280	0.356
	(0.033)***	(0.052)***	(0.036)***	(0.054)***
Pollution taxes$_{c,t\text{-}1}$ x	0.063	0.024	-0.118	-0.155
Q_2 of SO_x polluters	(0.083)	(0.028)	(0.129)	(0.131)
Pollution taxes$_{c,t\text{-}1}$ x	0.040	0.093	-0.039	-0.112
Q_3 of SO_x polluters	(0.031)	(0.064)	(0.057)	(0.031)***
Pollution taxes$_{c,t\text{-}1}$ x	0.125	-0.027	-0.007	-0.201
Q_4 of SO_x polluters	(0.030)***	(0.055)	(0.054)	(0.090)**
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observations	18,068	18,381	18,056	18,363
R^2	0.335	0.565	0.211	0.128

Table 7: Pollution taxes and R&D: Indicators of financing constraints

Table 7 reports OLS estimates of Equation 1 with *R&D* as the dependent variable. *Firm size* is the firm average natural logarithm of book value of total assets relative to the firm with with largest book value of total assets in the industry. *Large firm* is an indicator variable taking on the value one (zero) if the firm is above (below) the median in *Firm size*. *Size-age index* is based on Hadlock and Pierce (2010) and the *Whited-Wu index* is based on Whited and Wu (2006). Table 1 provides detailed variable definitions. The standard errors are clustered at the country level. ***, **, and * stand for significance at the 1%, 5%, and 10% levels.

	(1)	(2)	(3)	(4)
	Firm size		*Measures of financing constraints*	
Pollution taxes$_{c,t\text{-}1}$	-0.108	0.019	-0.230	0.037
	(0.029)***	(0.021)	(0.081)**	(0.031)
Sales$_{i,t}$	0.287	0.288	0.287	0.287
	(0.034)***	(0.034)***	(0.034)***	(0.034)***
Pollution taxes$_{c,t\text{-}1}$ *x*	0.282			
Firm size$_i$	(0.054)***			
Pollution taxes$_{c,t\text{-}1}$ *x*		0.081		
Large firm$_i$		(0.018)***		
Pollution taxes$_{c,t\text{-}1}$ *x*			-0.411	
Size-Age index$_i$			(0.077)***	
Pollution taxes$_{c,t\text{-}1}$ *x*				-0.642
Whited-Wu index$_i$				(0.122)***
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observations	36,449	36,449	36,449	36,431
R^2	0.413	0.401	0.391	0.432

Table 8: Pollution taxes and R&D: Access to external finance

Table 8 reports OLS estimates of Equation 1 with *R&D* as the dependent variable. *Large firms* (*Small firms*) consider firms above (below) the median in *Firm size*. *Market based finance* is an indicator variable taking on the value one if the firm has issued debt or equity sometime during the sample period. *Bank based finance* is an indicator variable taking on the value one if the firm has an average long term debt-to-assets ratio of at least 0.10 over the sample period and zero in *Market based finance*. Table 1 provides detailed variable definitions. The standard errors are clustered at the country level. ***, **, and * stand for significance at the 1%, 5%, and 10% levels.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	All firms	*Large firms*	*Small firms*	*All firms*	*Large firms*	*Small firms*	*All firms*	*Large firms*	*Small firms*
Pollution taxes$_{c,t\text{-}1}$	0.050	0.074	-0.026	0.066	0.071	0.038	0.048	0.073	-0.028
	(0.017)***	(0.024)***	(0.021)	(0.020)***	(0.020)***	(0.031)	(0.017)***	(0.025)***	(0.021)
Sales$_{i,t}$	0.287	0.533	0.197	0.287	0.533	0.197	0.287	0.533	0.197
	(0.034)***	(0.084)***	(0.022)***	(0.034)***	(0.083)***	(0.022)***	(0.034)***	(0.084)***	(0.022)***
Pollution taxes$_{c,t\text{-}1}$ *x*	0.050	-0.007	0.149				0.050	-0.008	0.150
Market based finance$_i$	(0.070)	(0.124)	(0.031)***				(0.070)	(0.125)	(0.031)***
Pollution taxes$_{c,t\text{-}1}$ *x*				0.003	0.002	0.004	0.003	0.002	0.004
Bank based finance$_i$				(0.002)	(0.002)	(0.002)*	(0.002)	(0.002)	(0.002)*
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	36,449	18,428	18,021	36,449	18,428	18,021	36,449	18,428	18,021
R^2	0.494	0.732	0.348	0.467	0.732	0.227	0.495	0.731	0.348

Table 9: Pollution taxes and R&D: Aggregate industry evidence

Table 9 reports OLS estimates of Equation 2 with the sum of country-industry *R&D* ($\sum R\&D_{cj,t}$) as dependent variable. All regressions include country-industry fixed effects and column 1-2 (3) include year (country-year) fixed effects.The standard errors are clustered at the country level. ***, **, and * stand for significance at the 1%, 5%, and 10% levels.

	(1)	(2)	(3)
Pollution taxes$_{c,t\text{-}1}$	1.019	-0.041	
	(0.483)**	(0.182)	
$\sum Sales_{cj,t}$	0.384	0.381	0.407
	(0.063)***	(0.063)***	(0.072)***
Pollution taxes$_{c,t\text{-}1}$ *x*		0.022	-0.012
Q_2 *of* SO_x *polluters*		(0.143)	(0.306)
Pollution taxes$_{c,t\text{-}1}$ *x*		0.568	-0.573
Q_3 *of* SO_x *polluters*		(0.584)	(1.396)
Pollution taxes$_{c,t\text{-}1}$ *x*		3.363	2.910
Q_4 *of* SO_x *polluters*		(1.370)**	(1.020)***
Country-industry f.e.	Yes	Yes	Yes
Year fixed effects	Yes	Yes	No
Country-year fixed effects	No	No	Yes
Observations	4,453	4,453	4,453
R^2	0.313	0.232	0.315

Table 10: Effects of pollution taxes on the aggregate development of air pollution abatement technologies

Table 10 reports OLS estimates of Equation 3 with *Patent count* as the dependent variable. *Patent count* measures the stock of triadic patents in pollution abatement technologies in columns 1-3 and the stock of all other triadic patents in columns 4-6. All regressions include country and year fixed effects. The standard errors are clustered at the country level. ***, **, and * stand for significance at the 1%, 5%, and 10% levels.

	(1)	(2)	(3)	(4)	(5)	(6)
	Counts of triadic patents in:					
	Air pollution abatement			*Non-air pollution abatement*		
Pollution taxes$_{c,t-1}$	0.054	0.056	0.057	0.020	0.013	0.014
	(0.026)*	(0.022)**	(0.022)**	(0.016)	(0.009)	(0.009)
Stock of air pollution abatment patents$_{c,t-1}$	0.244	0.220	0.220	0.032	0.002	0.003
	(0.084)***	(0.094)**	(0.095)***	(0.033)	(0.024)	(0.025)
Stock of non-air poll. abatment patents$_{c,t-1}$	0.148	0.005	-0.001	0.785	0.652	0.644
	(0.078)*	(0.075)	(0.098)	(0.065)***	(0.086)***	(0.104)***
Public environmental R&D-to-GDP$_{c,t-1}$		0.140	0.142		0.057	0.058
		(0.062)**	(0.061)**		(0.031)*	(0.030)*
GDP per capita$_{c,t-1}$			0.058			0.074
			(0.537)			(0.345)
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	371	358	358	371	358	358
R^2	0.822	0.662	0.652	0.988	0.984	0.983

A Appendix tables and figures

Table A.1: Observation counts and country level rates of pollution taxes

Table A.1 reports number of observations by country in the full sample (column 1) and average *Pollution taxes* by country (column 2). Table 1 provides detailed variable definitions.

	Number of observations	**Pollution tax Mean (1990-2012)**
Australia	1,898	0.88
Austria	296	0.00
Belgium	354	0.00
Canada	3,160	0.96
Denmark	493	4.30
Finland	717	0.00
France	1,400	0.98
Germany	2,003	0.00
Greece	292	0.00
Ireland	231	0.00
Italy	385	1.76
Japan	19,167	6.00
Korea	296	4.73
Netherlands	412	0.00
Norway	337	0.00
Spain	128	1.34
Sweden	1,256	0.00
United Kingdom	4,079	0.00
Total	36,904	–

Table A.2: Evaluating stability of SO_x emission measure

Table A.2 lists 17 ISIC industries from OECD's data portal with information on the average tonnes of SO_x emission per one million local currency of output during 2000-2012 (in columns named "**So_x emission**") for Italy, the Netherlands, and Denmark respectively. The columns "**Rank**" lists the industries ranked in order of SO_x emission for Italy, the Netherlands, and Denmark respectively. The final two columns display the rank of SIC three-digit industries (using US industries from our baseline sample) in terms of most (least) polluting industry from Table 3.

		Italy		**Netherlands**		**Denmark**		**Pollution rank**	
ISIC	**Industry**	**SO_x emission**	**Rank**	**SO_x emission**	**Rank**	**SO_x emission**	**Rank**	**Most**	**Least**
19	Coke and refined petroleum products	1.608	1	1.022	1	0.041	2	2	
23	Other non-metallic mineral products	1.107	2	0.452	3	0.122	1	1, 4, 7	
24	Basic metals	0.379	3	0.855	2	0.002	8	5, 6	
20	Chemicals and chemical products	0.268	4	0.087	4	0.029	3	3, 9, 10	
17	Paper and paper products	0.087	5	0.015	6	0.006	7		
16	Wood and of products of wood and cork	0.045	6	0.005	9	0.010	5		
22	Rubber and plastic products	0.043	7	0.001	16	0.001	12		
21	Basic pharmaceutical products	0.040	8	0.005	10	0.003	6		
10-12	Food products, beverages and tobacco products	0.032	9	0.012	7	0.029	4	8	7
31-33	Furniture	0.023	10	0.002	12	0.001	9		
13-15	Textiles	0.016	11	0.004	11	0.001	13		
28	Machinery and equipment n.e.c.	0.005	12	0.008	8	0.001	11		
29-30	Motor vehicles and other transport equipment	0.002	13	0.001	15	0.000	14		
26	Computer, electronic and optical products	0.000	14	0.002	14	0.000	16		1, 4, 5, 6
18	Printing and media	0.000	15	0.001	17	0.000	15		2
27	Electrical equipment	0.000	16	0.023	5	0.000	17		9
25	Fabricated metal products	0.000	17	0.002	13	0.001	10		3, 10

Table A.3: Industry pollution and immobility: Firm distribution

Table A.3 reports observation counts across pollution intensity and industry immobility. Firms are sorted in to high (low) pollution if they are located in industries above (below) the median in *SO_x emission* and firms are sorted in immobile (mobile) if they are located in industries above (below) the median in *Industry immobility*.

	High pollution	**Low pollution**	**All firms**
Immobile	14,849	3,622	18,471
Mobile	8,331	10,102	18,433
All firms	23,180	13,724	36,904

Table A.4: Pollution taxes and R&D investment: Alternative samples

Table A.4 reports OLS estimates of Equation 1 with *R&D* as the dependent variable. A large country has more than 3,000 observations (Japan, UK and Canada) and a small country has less than 300 observations (Spain, Ireland, Greece, Austria and Korea). No change SO_x tax are the countries without any changes in the pollution tax during the sample period (see Table A.1). All regressions include firm and year fixed effects. Table 1 provides detailed variable definitions. The standard errors are clustered at the country level. ***, **, and * stand for significance at the 1%, 5%, and 10% levels.

	(1)	(2)	(3)	(4)	(5)	(6)
	No Japan	*No UK*	*No Canada*	*No three largest*	*No smallest*	*No change SO_x tax*
Panel A: Baseline						
Pollution taxes$_{c,t\text{-}1}$	0.039	0.071	0.072	0.034	0.076	0.040
	(0.016)**	(0.019)***	(0.020)***	(0.020)	(0.021)***	(0.014)**
Sales$_{i,t}$	0.295	0.288	0.298	0.318	0.305	0.263
	(0.039)***	(0.040)***	(0.045)***	(0.061)***	(0.037)***	(0.035)***
Panel B: Identification						
Pollution taxes$_{c,t\text{-}1}$	0.005	0.032	0.031	-0.002	0.032	0.004
	(0.012)	(0.012)**	(0.012)**	(0.017)	(0.012)**	(0.011)
Sales$_{i,t}$	0.295	0.287	0.297	0.317	0.395	0.262
	(0.039)***	(0.040)***	(0.045)***	(0.061)***	(0.037)***	(0.035)***
Pollution taxes$_{c,t\text{-}1}$ x	0.012	0.030	0.027	0.002	0.028	0.015
Q_2 of SO_x polluters	(0.024)	(0.024)	(0.026)	(0.030)	(0.024)	(0.025)
Pollution taxes$_{c,t\text{-}1}$ x	0.052	0.060	0.054	0.046	0.094	0.049
Q_3 of SO_x polluters	(0.033)	(0.045)	(0.044)	(0.026)*	(0.056)	(0.039)
Pollution taxes$_{c,t\text{-}1}$ x	0.064	0.068	0.077	0.072	0.071	0.068
Q_4 of SO_x polluters	(0.016)***	(0.016)***	(0.013)***	(0.013)***	(0.014)***	(0.016)***
Firm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Observations	17,280	32,470	33,495	10,347	35,207	11,660

Table A.5: Pollution taxes and R&D investment: Alternative dependent variables

Table A.5 reports OLS estimates of Equation 1 with *R&D-to-assets* in columns 1-2, *log(CAPX)* in column 3, and *CAPX-to-assets* in column 4 as the dependent variable. All regressions include firm fixed effects. Columns 1 include year fixed effects and columns 2-4 include country-year fixed effects. Table 1 provides detailed variable definitions. The standard errors are clustered at the country level. ***, **, and * stand for significance at the 1%, 5%, and 10% levels.

	(1)	(2)	(3)	(4)
	R&D-to-assets		*log(CAPX)*	*CAPX-to-assets*
Pollution taxes$_{c,t\text{-}1}$	0.002			
	(0.001)**			
Pollution taxes$_{c,t\text{-}1}$ *x*	0.000	0.001	-0.050	-0.005
Q_2 *of* SO_x *polluters*	(0.002)	(0.003)	(0.029)	(0.001)***
Pollution taxes$_{c,t\text{-}1}$ *x*	-0.002	-0.001	0.000	-0.003
Q_3 *of* SO_x *polluters*	(0.001)*	(0.001)	(0.015)	(0.001)***
Pollution taxes$_{c,t\text{-}1}$ *x*	0.003	0.004	0.000	-0.003
Q_4 *of* SO_x *polluters*	(0.001)***	(0.001)***	(0.012)	(0.001)**
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	No	No	No
Country-year fixed effects	No	Yes	Yes	Yes
Observations	36,432	36,432	39,247	39,231
R^2	0.017	0.036	0.697	0.040

Table A.6: Pollution taxes and R&D investment: Omitted economic shocks

Table A.6 reports OLS estimates of Equation 1 with *R&D* as the dependent variable. All regressions include firm fixed effects. Columns 1 and 3 include year fixed effects and columns 2 and 4 include country-year fixed effects. *(1997-2001)* is an indicator variable taking on the value one for all countries and firm-years (zero) during 1997-2001 (1990-1996 and 2002-2012). Table 1 provides detailed variable definitions. The standard errors are clustered at the country level. ***, **, and * stand for significance at the 1%, 5%, and 10% levels.

	(1)	(2)	(3)	(4)
$Sales_{i,t}$	0.289	0.247	0.287	0.244
	(0.033)***	(0.027)***	(0.034)***	(0.029)***
(1997-2001) x	-0.013	-0.029	-0.019	-0.012
Q_2 *of* SO_x *polluters*	(0.032)	(0.033)	(0.033)	(0.035)
(1997-2001) x	0.014	0.001	0.006	0.009
Q_3 *of* SO_x *polluters*	(0.013)	(0.013)	(0.033)	(0.035)
(1997-2001) x	-0.024	-0.017	-0.011	-0.001
Q_4 *of* SO_x *polluters*	(0.032)	(0.026)	(0.030)	(0.026)
Pollution $taxes_{c,t\text{-}1}$			0.030	
			(0.012)**	
Pollution $taxes_{c,t\text{-}1}$ *x*			0.028	0.027
Q_2 *of* SO_x *polluters*			(0.024)	(0.013)*
Pollution $taxes_{c,t\text{-}1}$ *x*			0.060	0.059
Q_3 *of* SO_x *polluters*			(0.044)	(0.023)**
Pollution $taxes_{c,t\text{-}1}$ *x*			0.067	0.070
Q_4 *of* SO_x *polluters*			(0.017)***	(0.015)***
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	No	Yes	No
Country-year fixed effects	No	Yes	No	Yes
Observations	38,184	38,184	36,449	36,449
R^2	0.564	0.532	0.437	0.462

Table A.7: Pollution taxes and R&D investment: Industry share in economy

Table A.7 reports OLS estimates of Equation 1 with *R&D* as the dependent variable. All regressions include firm and year fixed effects. Table 1 provides detailed variable definitions. The standard errors are clustered at the country level. ***, **, and * stand for significance at the 1%, 5%, and 10% levels.

	(1)	(2)	(3)	(4)
$Sales_{i,t}$	0.288	0.289	0.288	0.288
	(0.035)***	(0.045)***	(0.035)***	(0.045)***
Industry share R&D$_{cj,t}$	0.466		0.464	
	(0.343)		(0.337)	
Industry share Employment$_{cj,t}$		0.535		0.519
		(0.199)***		(0.199)***
Pollution taxes$_{c,t\text{-}1}$	0.070	0.049	0.032	0.011
	(0.020)***	(0.017)**	(0.014)**	(0.010)
Pollution taxes$_{c,t\text{-}1}$ *x*			0.027	0.016
Q_2 *of* SO_x *polluters*			(0.024)	(0.010)
Pollution taxes$_{c,t\text{-}1}$ *x*			0.065	0.045
Q_3 *of* SO_x *polluters*			(0.042)	(0.041)
Pollution taxes$_{c,t\text{-}1}$ *x*			0.062	0.074
Q_4 *of* SO_x *polluters*			(0.019)***	(0.014)***
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observations	36,449	30,351	36,449	30,351
R^2	0.496	0.531	0.462	0.508

Table A.8: Pollution taxes and R&D: Robustness external finance

Table A.8 reports OLS estimates of Equation 1 with *R&D* as the dependent variable. All regressions include firm and year fixed effects. A firm is classified as *low* (*high*) if the firm is below (above) the median in *Size-age index* or *Whited-Wu index*. The standard errors are clustered at the country level. ***, **, and * stand for significance at the 1%, 5%, and 10% levels.

	(1)	**(2)**	**(3)**	**(4)**
	Size-age index		*Whited-Wu index*	
	Low	*High*	*Low*	*High*
Pollution taxes$_{c,t\text{-}1}$	0.073	-0.026	0.075	0.020
	(0.025)***	(0.020)	(0.021)***	(0.018)
Sales$_{i,t}$	0.535	0.196	0.553	0.187
	(0.084)***	(0.022)***	(0.088)***	(0.021)***
Pollution taxes$_{c,t\text{-}1}$ *x*	-0.005	0.147	-0.041	0.095
Market based finance$_i$	(0.125)	(0.032)***	(0.108)	(0.053)*
Pollution taxes$_{c,t\text{-}1}$ *x*	0.002	0.000	0.002	0.000
Bank based finance$_i$	(0.002)	(0.003)	(0.002)	(0.002)
Firm fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes
Observations	18,454	17,995	18,368	18,081
R^2	0.733	0.346	0.762	0.250