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Do market-based instruments really induce more environmental R&D? A test using US panel data

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Abstract

National governments are considering increasing spending on greenhouse gas mitigation R&D by billions of dollars per year at a time when many nations face severe fiscal austerity. This study investigates empirically whether it is realistic to expect market-based environmental policy instruments to stimulate a lot of environmental R&D spending on their own. The hypothesis developed is that increasingly market-based forms of environmental regulation might bring a conditional reduction in the level of environmental R&D spending, all else being equal; and that increasingly market-based approaches to climate mitigation policy may not necessarily induce the large amounts of environmental R&D spending that some corners of the induced innovation literature might predict. The hypothesis is tested using panel data on environmental R&D spending for 30 industry groups over 22 years. The evidence suggests the degree to which the prevailing policy regime embraced market forces may have diminished the R&D-motivating effect of the environmental regulatory burden. This implies that the quest to raise environmental R&D spending may be a good thing in its own right, and that the quest to incorporate market principles and institutions into environmental policy design may also be a good thing, but that market-based policies may undermine the incentives that firms have to invest in environmental R&D.

Outline

1. Introduction

A large increase in research and development (R&D) spending for greenhouse gas (GHG) control is one element being proposed for a post-Kyoto climate stabilisation framework (Atkinson et al. 2011; Hoffert et al. 2002; Mowrey, Nelson and Martin 2009; US National Academy of Sciences 2009; Prins and Rayner 2007; Prins et al. 2010; Rees 2006). One proposal for the US involves scaling-up climate-related R&D spending to the levels that were in place under the Manhattan Project during the 1940s (Mowrey, Nelson and Martin 2009). Another proposal involves increasing US federal spending on clean energy R&D from four billion to 25 billion dollars annually for a decade or more (Hayward et al. 2010). Another involves raising R&D spending for GHG abatement technologies to eight billion dollars per year for the next nine years (Newell 2008). In Europe, the low and volatile price of emission permits under the Emission Trading Scheme (ETS) does not appear to be inducing as much clean energy technology development and deployment as policymakers might like. This has led to calls in Europe for greater public support for climate mitigation R&D and accelerated technology development through R&D tax credits, direct public spending on basic R&D and, in the UK, the introduction of a CO2 emissions floor price (Delbosc and de Perthuis 2009; HMT and HMRC 2011; Nordhaus 2011; Hepburn and Stern 2008).

These proposals tend to be justified by the idea that even under an environmental policy instrument that puts a price on the environmental externality, like the EU ETS, firms will still under-invest in the activities that create the technical knowledge needed for low-cost GHG abatement. Under-investment occurs because a large share of the returns from R&D of any type, climate-related or otherwise, tends to accrue to society rather than to the firms making the investment. This means that the returns to R&D are almost never fully privately appropriable (Antonelli 2002; Hall and Van Reenen 2000). Since markets alone do not reward firms sufficiently for investing in R&D due to these positive externalities, the argument goes, governments should intervene with policies like carbon price supports and subsidies to climate-related R&D to correct the externality.

This study investigates, empirically, the effect that market-based policy instruments like the ETS in Europe and the proposed carbon tax in the US (Nordhaus

2011) should realistically be expected to have in their own right on environmental R&D spending levels. It tests the conditioning effect that greater orientation towards markets as an institutional form for delivering environmental policy goals has had historically on the R&D-motivating effect of the environmental regulatory burden. It uses panel data from the US National Science Foundation (NSF) covering 22 years and about 30 industry groups. It is argued that the length and placement of these 22 years gives enough variation in the degree to which the policy regime embraced the principles of markets to test the conditioning effect of orientation to markets on the level of formal technical knowledge creation by firms for the specific purpose of abating conventional pollutants.

The evidence suggests that, in the context of the US for the 22 years in question, the more heavily policymakers relied on using economic incentives to motivate environmental compliance, the less of this specific type of environmental R&D firms chose to conduct per dollar of environmental regulatory burden. The NSF data show that US industry in aggregate steadily decreased its level of environmental R&D spending from about 1979 onward at the same time as increasingly market-based forms of regulation were legitimising less original forms of compliance and less original forms of technical knowledge in compliance. Co-occurrence is of course a far cry from causality and various tests and robustness checks are performed of this relationship.

One possible explanation for the result that emerges from the preponderance of these tests is that firms may have made greater use of informal technical knowledge acquired elsewhere, from suppliers or competitors perhaps, in place of producing original knowledge through R&D of their own. This informally-acquired compliance knowledge may have become increasingly permissible to use under an increasingly market-based policy regime. Informal ways of acquiring knowledge may have included learning by doing and using, gleaning knowledge from the patent record, acquiring knowledge in the form of labour, imitating knowledge-embodying practices of competitors, buying knowledge embedded in new equipment, creating informal knowledge through tinkering, purchasing technical blueprints, and reverse-engineering products and processes (Arrow 1962; Boerner et al. 2001; Archibugi, Howells and Michie 2003). These acquisition methods might have supplanted the need for regulation-affected firms to conduct environmental R&D of their own.

Through a detailed and critical reading of the theoretical literature on policy instrument design and innovation, Section 2 argues that there is not as much evidence as might be expected *against* the hypothesis that increasingly market-based forms of instrument design conditionally weakens the R&D-motivating effect of the environmental regulatory burden. Section 3 sets up the empirical, explains the specific nature of the 'environmental' R&D data fitted to the model, and presents the regression results. Section 4 discusses the implications of this evidence for the environmental technological change literature and for policy.

2. Theory and hypothesis

There is broad agreement that policy instrument designs that give firms economic incentives to improve their environmental performance are more economically efficient than policy instrument designs that do not (Downing and White 1986; Hahn and Hester 1989; Jung, Krutilla and Boyd 1996; Kemp and Pontoglio 2011; Magat 1979; Milliman and Prince 1989; Popp 2010). This agreement tends to break down around the question of why, exactly, economic instruments are more efficient. The exact reason *why* economic instruments are more efficient is important. If economic instruments are more efficient because they stimulate firms to deal with the environmental regulatory burden by creating new formal knowledge and technology through their own R&D, then subsidizing the creation of knowledge and technology through R&D might be justified. But if economic instruments are more efficient because they stimulate firms to deal with the regulatory burden by imitating, adopting and otherwise acquiring knowledge and technology that substitutes for the need to perform formal R&D, then an R&D subsidy is likely to be less effective and possibly ineffective and wasteful.

The idea that economic instruments are efficient for the first reason, because they induce a large amount of knowledge and technology creation through formal R&D, is a relatively recent phenomenon. Orr (1976) argued that the uniform emission standards popular with governments in the early 1970s should be abandoned in favour of instruments like effluent taxes and permits. He reasoned that economic instruments give producers incentives for 'continuous and detailed technological adaptation to the impacts on the environment of growth' (442). He stated that one criterion for evaluating the desirability of different policy instruments should be the extent to which the instrument gives firms the liberty to adapt their production methods to the constantly changing price of inputs, including the changing price of environmental inputs brought about by growth-induced resource scarcity. Orr was not arguing that economic instruments necessarily stimulate a great deal of R&D in response to scarcity, but rather that they give firms the fullest possible leeway to adapt to unrelenting and often unpredictable change. Adaptation for Orr could include R&D if the firm sees fit, but it could also include many other forms of adaptation that involve performing little or no R&D.

The studies that followed Orr comparing the efficiency of different instruments are inconsistent in the amount of credit they give to formal R&D in achieving pollution reduction outcomes under the instruments. The conditioning effect of the instrument design on the way that polluters respond to the environmental regulatory burden is often not made explicit. Downing and White (1986) for example looked at the effect of different instrument types on 'innovation'. They found that economic instruments give firms the most consistently adequate incentives to innovate. They defined innovation as:

> 'a discovery that will reduce the cost of controlling emissions… [which] normally involves an initial cost or investment (e.g., research and development expenses) and then a subsequent cost reduction or saving if the innovation is employed.' (1986: 19)

For Downing and White, 'innovation' meant much the same thing as R&D. Downing and White attribute a significant part of the emission reductions brought about under economic instruments to R&D. This is inconsistent with what Orr was arguing. Orr was arguing that economic instruments are efficient simply because they give firms the leeway to adapt to change in whatever way necessary, by whatever method. Downing and White imply that economic instruments are efficient because they give firms the strongest incentive to positively 'innovate' through 'e.g., research and development'. However, there are many effective ways to innovate and undergo change that do not involve performing R&D.

Adopting pollution control technology can be a method of compliance that involves less formal R&D than original inventive activity (Stoneman 2002; Popp 2006). Milliman and Prince (1989) modelled the effect of the different instrument types on total social gains from a broader process involving invention, diffusion and a ratcheting-down response by the regulator. In this three-stage process economic instruments yielded the largest social gains but with a caveat: suppliers. Milliman and Prince found that suppliers are special because they do not discharge emissions themselves. Suppliers have very weak incentives to perform R&D under economic instruments because there is no control authority present to require polluting firms to adopt the new control technology that suppliers invent. The incentives suppliers have to perform R&D under rigid instruments essentially collapse under economic instruments (1989: 256). Milliman and Prince were among the first to recognise that economic instruments might actually *undermine* new innovation activity by some types of firms insofar as innovation involves formal R&D.

Jung, Krutilla and Boyd (1996) also found that economic instruments are the most efficient. Again it is important to look carefully at the reason given for why economic instruments are most efficient. Jung, Krutilla and Boyd attribute efficiency to the 'development and adoption of advanced pollution abatement technology' (95). They model the *effect* of this force as a decline in the marginal cost of abatement faced by individual firms (see their footnote 5). The cost decline is assumed to come from the knowledge and technology created by the R&D that economic instruments induce but the creation, accumulation and/or application of knowledge through formal R&D is not explicitly modelled.

Other theoretical work has suggested that economic instruments in their own right may not trigger very much new pollution abatement technology adoption. Malueg (1987) directly challenged the idea that the efficiency of permit trading rests on the incentives it creates for firms to adopt new pollution control technology. Malueg's key insight was that when a firm faces an external permit price set by competitive market forces, this price can be so low that it makes it uneconomical for the firm to adopt new technology at all, since the most economical way to comply is by buying cheap permits. Writing in 1987, three full years before US lawmakers created the SO2 permit trading program, Malueg predicted that:

> ' . . . since the demand for the more effective pollution abatement technology may fall with the introduction of trading, it is possible that investment in research and development of new pollution abatement technologies may also fall after trading is introduced.' (1987: 56)

Here, Malueg predicts that environmental R&D spending might actually fall under a permit trading program. This was almost exactly in line with what the empirical evidence tells us actually happened after 1990 under the US SO2 permit trading program (Popp 2002; Taylor, Rubin and Hounshell 2005; Sanyal 2007). The permit trading program altered the incentives firms had to perform R&D, both the quantity and the nature of the problems the R&D was oriented to solving. The new incentive regime seems to have resulted in affected firms cutting their environmental R&D spending levels significantly.

Other studies have found that economic instruments can conditionally or unconditionally lessen the role that R&D plays in the compliance process. Dreisen (2003) argued that permit trading leads the firms with the very cheapest abatement opportunities to exploit these opportunities with ‘routine’, ‘off-the-shelf’, and ‘adequate’ technology of the type that already exists and does not need to be developed anew through R&D. Complying in this way does little to push out the technological frontier in pollution control technology, he argued (2003: 10098-10101). This is because the firms that exploit these opportunities using routine technologies then sell the permits at prices that undermine other polluters’ incentives to develop or adopt new technology. Similarly, Parry, Pizer and Fischer (2000) compared the welfare gains from two policy options for dealing with a hypothetical pollutant: (a) large-scale investment in R&D to bring down the cost of abatement; or (b) implementing a policy that simply corrects the externality. Parry, Pizer and Fischer found that the welfare gains from R&D are typically smaller (in the authors words ‘perhaps much smaller’ (2000:15)) than the gains from simply correcting the externality. The reason is that it takes a long time and a great deal of R&D spending to accumulate enough knowledge to substantially lower the cost of abatement. Further, in the original DICE model, Nordhaus (1994) investigated where GHG emission reductions are likely to come from over the next 100 years. Nordhaus found that some of the largest reductions are likely to come from global energy demand reduction and fuel switching from coal to natural gas, rather than from radically new forms of energy generation or pollution control.

So far this analysis has looked critically at the role that formal environmental R&D plays in the environmental compliance process under instruments which utilise price signals and incentives. *It has been critical of the strength of the role that formal*

R&D for pollution control plays in this process, not of the efficiency of market-based instruments themselves.

The empirical focus of this paper is on conventional pollution emission control in the United States. US regulators have relied increasingly on price signals, incentives, competition and market-based forms of organisation in the design of policy instruments in this sphere during the last 40 years. The extent to which the environmental policy regime embraces market forces can be thought of in terms of the amount of control that a regulator gives to firms, polluters and suppliers both, and to the market institutions that they are embedded in, to direct the way that the environmental policy aim set out by the regulator is achieved. The regulator can turn over control in at least four different 'dimensions' of environmental policy: the temporal dimension, the spatial dimension, the between-firm/between-facility dimension, and the abatement method dimension. The transfer of control in these four dimensions in the US during the last 40 years is illustrated through the policy design changes toward conventional emissions from automobiles and toward sulphur dioxide emissions from electric power plants. *These two sources account for 84 per cent by weight of all regulated air pollution emissions in the US between 1970 and 2000* and so may not be unrepresentative of a more general experience (US EPA 2008).

With respect to automobile emissions, in 1970 regulators directed the automobile manufacturers to reduce carbon monoxide (CO), hydrocarbon (HC) and oxides of nitrogen (NOx) emissions from all the new vehicles they sold in the US by 90 per cent by model year 1976 (US Congress 1970; Reitze 2001). In the 'temporal' dimension regulators gave polluters a fixed period of five years to meet the reductions and threatened to impose very large non-compliance penalties if the deadline was not met. In the 'spatial' dimension regulators required the automobile manufacturers to sell 90 per cent cleaner vehicles both in major cities with intense ambient air quality problems and high damage costs, and also in rural areas with no significant air quality problems and low damage costs. Regulators allowed almost no latitude for the degree of reductions to vary across space. In the 'between-firm' dimension, virtually every vehicle from every automobile manufacturer had to meet the standard. Neither within-company fleet-averaging nor between-company emission credit trading was allowed in the early days (White 1976). In the 'abatement method' dimension regulators strongly encouraged the automobile manufacturers to meet the standards by developing stand-alone pollution control technology like catalytic converters

(Bittlingmayer 1987; Goldstein and Howard 1980; US Congress 1970; US Congress 1977).

There is considerable evidence of a move toward market forces along all four of these dimensions in the overhaul by Congress of automobile pollution control policy in the 1990 Clean Air Act Amendments. In the temporal dimension regulators required that new exhaust pipe emission standards be met through two smaller step changes, with deadlines in 1994 and 2004, rather than through one big step change by a single date. In the spatial dimension policymakers wrote into the 1990 Amendments a provision that allowed the automobile manufacturers to differentiate the vehicles they produced for California, and for the other 49 states. This introduced spatial differentiation by only requiring the vehicles meeting the most stringent standards (the so-called ultra-low emission vehicles (ULEVs) and zero emission vehicles (ZEVs)) to be sold in California, where the damage costs were generally highest. In terms of abatement methods, Congress included a ‘fuel neutrality’ provision in the 1990 Amendments that let the automobile manufacturers design ULEVs and ZEVs around virtually any clean alternative fuel or fuel combination they chose. This left market forces to decide the most economical clean fuel. In the inter-firm dimension the 1990 Amendments set out new requirements on the content (benzene) and characteristics (volatility) of fuels for the most heavily polluted regions in the country. The legislation created a program allowing oil companies, fuel importers, fuel refiners and fuel blenders to earn tradable credits for exceeding the mandatory fuel specifications.

A similar move toward market principles and policy regime flexibility is in evidence in the case of sulphur dioxide control from electric power plants. The 1970 CAA Amendments stated that any new fossil fuel fired boiler proposed to be built in a heavily polluted area could emit no more than 1.2 pounds of SO2 per million British thermal units (MMbtu) of heat input (US Congress 1970; Reitze 2001). This standard was fixed and largely inflexible. Any firm proposing a new boiler or plant expansion that did not meet this standard in a heavily polluted area would be denied planning permission by the planning authority. In terms of abatement methods, regulators also set out rules that more or less required new and expanding plants as well as some existing plants to meet the standard by installing flue gas desulphurisation units. Regulators put these requirements in place even though many utilities would have preferred the cheaper and simpler abatement method of burning lower-sulphur fuels like lignite coal and natural gas (Joskow 1998).

By the late 1970s regulators had begun to allow new and expanding power plants to comply with the emission standards in an increasingly wide and flexible range of ways (US EPA 2001; US congress 1977). In the between-firm dimension, the 'offset mechanism' introduced in the 1977 CAA Amendments allowed new and expanding plants to be granted planning permission if they were able to purchase sufficient emission reduction credits (ERCs) from existing sources to offset the new emissions caused. Also within firms, 'netting' rules introduced in 1980 allowed new and expanding plants to avoid triggering the 1.2 MMbtu standard as long as they could keep net facility emissions below the trigger threshold. They could do this for example by decreasing emissions from elsewhere in the same facility at the same time. 'Bubbling' came into practice in 1980. The term 'bubbling' means that a facility with several emission points, like a petroleum refinery, could apply to the EPA to treat all their emission points together as if they were subject to a single aggregate limit. In the temporal dimension, regulators began allowing plant operators to 'bank' emission reductions from the late 1970s. Banking let plant operators save as credits the surplus emission reductions they earned in low abatement cost time periods, and apply these later in high abatement cost time periods. The Environmental Protection Agency (EPA) formalised the rules for offsets, netting, bubbles and banking in its 1986 Final Emission Trading Policy Statement (US EPA 1996; 2001). In the abatement method dimension, the SO2 permit trading program set up in 1990 more or less eliminated the regulator's preference for scrubbers that was built into the prior, more rigid framework. Trading led to many plant operators abandoning flue gas desulphurisation for a range of other lower cost abatement methods including fuel switching and load shifting.

In these two examples, the regulators' approach of setting rigid timelines for compliance tended to give way to staged or negotiable timelines. This flexibility removed some of the constraints on firms that would have prevented them from complying in the way that market forces might dictate. Regulators tended to move from a position of insisting on emission standard uniformity across space toward allowing firms to vary their abatement strategies across geographic space and across individual establishments and pollution points under the aegis of a single firm. The authority to decide what constituted an acceptable technical approach to controlling pollution tended to shift away from the regulatory authority toward the firms themselves and the market forces that shaped the firms' behaviour.

Taken in combination with the critical review of the role that formal R&D plays in outcomes under market-based instruments, these policy examples motivate the hypothesis tested empirically in the next section. The hypothesis is that one reason for the efficiency of market-based instruments is that they give polluting firms implicit permission to avoid the most expensive forms of compliance, that they would otherwise be required to undertake under inflexible regulation, *including the requirement to perform expensive and unnecessary knowledge and technology creation activities through formal environmental R&D.* Market-based instruments may derive some of their efficiency not so much from the fact they induce a lot of new formal knowledge and technology creation for environmental protection through R&D, but because they give firms a way out from having to perform unnecessarily expensive searches for knowledge and technology when inexpensive low- or no-R&D techniques already exist.

Hypothesis: The degree to which the environmental policy regime embraces market-based design principles conditions the effect that the regulatory burden has on the level of environmental R&D spending. The more the policy regime allows firms and market forces to direct how the regulatory requirement is dealt with, the lower the level of environmental R&D affected firms will choose to perform.

3. Empirical approach

The hypothesis is tested in the context of the industrial environmental R&D performed in the US during the period 1972-1994. The model is fitted to data from the NSF’s Industrial Research and Development Information System (IRIS) database and from the US EPA’s Pollution Abatement and Control (PAC) expenditure reports. All of the environment-related data were gathered by NSF and EPA under a common conceptual and statistical framework for measuring the economic impact of environmental programs in the US (see Cremeans 1977 for a discussion of this framework). The dataset contains repeat observations over 22 continuous years for 30 two- and three-digit industry groups (SIC 20–39). The NSF and the EPA stopped gathering the environmental R&D data after the mid-1990s which is why the time series stops at 1994 (NSF 1999a). All spending data used in the estimations were deflated to real 1992 dollars using the BEA’s fiscal year GDP price index. An interaction strategy is used to test the conditioning effect of the degree to which the prevailing environmental policy regime embraced market principles in its design, on the slope of the relationship between PAC expenditure and environmental R&D expenditure.

a. Empirical model

In the reduced form model the level of environmental R&D expenditure is regressed on a vector of independent variables, ***Z***, plus a classical error term:

$$y = \mu + \beta \mathbf{Z} + \varepsilon$$

The first variable of interest in the vector ***Z*** measures the level of regulatory burden as annual (PAC) expenditure. Also of interest in vector ***Z*** is a set of period dummies. These dummies are used as rough indicators of the degree to which the policy regime prevailing at the time that the PAC expenditure was made was market-based. In the estimations, two of the time period dummies are separately interacted with PAC expenditure. These variables are discussed in detail below.

The interaction strategy of PAC expenditure with the regime dummies captures the forces that shape the incentive that firms had to perform environmental R&D more completely than either variable would on its own. The PAC expenditure variable measures the *level* of the regulatory burden but contains no information about the legal restrictions that the prevailing policy regime placed on how firms were allowed to deal with the burden. On the other hand, the policy regime dummies are expected to contain information about how firms were allowed to deal with the regulatory burden, but they do not contain information about the level of the regulatory burden itself. The interaction implements the test of the hypothesis that the degree to which the prevailing policy regime embraces market principles *conditions the amount of environmental R&D that is performed in response to a given PAC burden*. PAC expenditure is expected to exert a positive effect on the level of environmental R&D expenditure in an unconditional relationship. When PAC expenditure is interacted with the dummy for the presence of the market-based policy regime, PAC expenditure is still expected to exert a positive effect on the level of environmental R&D expenditure, but it is expected that its effect will be diminished by the conditioning effect of the regime.

Industry fixed effects control for unobserved time-constant variation in the level of environmental R&D expenditure specific to each industry group. Unobserved time-constant variation might arise from the different levels of opportunity for technological progress available in Drugs and medicine compared to Textiles and apparel, for example. Technological gains are likely to be more difficult and expensive in less dynamic industries (Jaffe and Palmer 1997; Fung 2004). With industry fixed effects the model takes the form:

$$y_{i,t} = \mu_i + \beta \mathbf{Z}_{i,t} + \alpha_i + \varepsilon_{i,t}$$

where i denotes industry group, t year, μ the intercept, α the industry group-specific fixed effect, and ε the error term capturing residual heterogeneity. β denotes the independent variable coefficients to be estimated.

The model is estimated in log-linear functional form. The log-linear specification gives the fit with the most homoscedastic error distribution. This was based on a comparison with a log-log specification where all continuous independent variables were logged; a log-log specification where only the independent variables of interest were logged; a linear-linear specification where no variables were logged; and a linear-log specification where all independent variables were logged. The log-linear form also gave the highest within-R-square value of the five functional forms (.234). The full empirical model takes the form:

$$(ln)Environmental\ R\&D\ spending_{i,t} = \mu_i + \beta_1 PAC\ spending_{i,t} + \beta_2 Mixed\ policy\ regime\ dummy_t + \beta_3 Market\text{-}based\ regime\ dummy_t + [\beta_4 PAC\ x\ mixed\ policy\ regime\ dummy_{i,t}] + [\beta_5 PAC\ x\ market\text{-}based\ regime\ dummy_{i,t} + \beta_6 Year_t + \beta_7 Employment_{i\ t} + \beta_8 Ordinary\ R\&D\ spending_{i,t} + \varepsilon_{i,t}$$

Each variable is discussed in turn.

b. Dependent variable

The dependent variable is *total spending on pollution abatement R&D by private industry and the federal government combined*. The model estimates the combined level of company and federal pollution abatement R&D together because private industry is expected to have heavily influenced the level of federal R&D spending and the way that this kind of R&D was conducted (NSF 2002). Sperling (2001: 253) for example found that the federal government channelled 2/3rds of a 300 million federal R&D program to develop cleaner automobiles in the early 1990s directly to three major US automobile manufacturers and to automotive supplier companies. The automotive industry performed this R&D on behalf of the federal government. Also, during the 1970s and 1980s when EPA's Office of Research and Development was developing flue gas desulphurisation technology for power plants, it performed much of its R&D in the field at electric utilities like the Tennessee Valley Authority (Cole 1997; EPA 1995). Field research put the federal R&D effort in direct contact with the pollution control problems industrial facilities were facing. It demonstrated the real world viability of the technology to would-be users in industry.

Since the main interest is to understand the determinants of private sector environmental R&D activity, a control for the presence of federal R&D activity in the dependent variable is later included in a robustness check.

'Pollution abatement R&D' has a very specific meaning in the context of the NSF questionnaire used to gather the data. Its meaning rests in turn on the meaning of 'pollutants'. Pollutants means:

> '…all the classes of measurable agents (forms of matter or energy) that are discharged to common-property media from a government or market-related activity so as to cause loss of welfare to a human receptor.' (Cremeans 1977: 102)

The dependent variable therefore includes R&D for controlling pollution emissions to any environmental medium (air, water, land, other) from automobiles, electric power plants and manufacturing facilities. It includes pollution in the form of solid waste, heat, noise or radiation. It only includes R&D for the purpose of eliminating the emission of pollutants to 'outside the firm's property or activities' as through R&D aimed at prevention, treatment or recycling (NSF 1999c: 10). Pollution abatement R&D explicitly *excludes* R&D for the purpose of improving environmental aesthetics; improving equipment durability; conserving energy or natural resources; or for increasing employee comfort, health or safety (NSF 1999c: 10-11).

The dependent variable also avoids the 'dual use' problem (Tucker 1994; OECD 1999) that tends to hamper empirical environmental technological change research. The NSF questionnaire instructs respondents to separate out R&D spending for pollution abatement from R&D spending for other purposes:

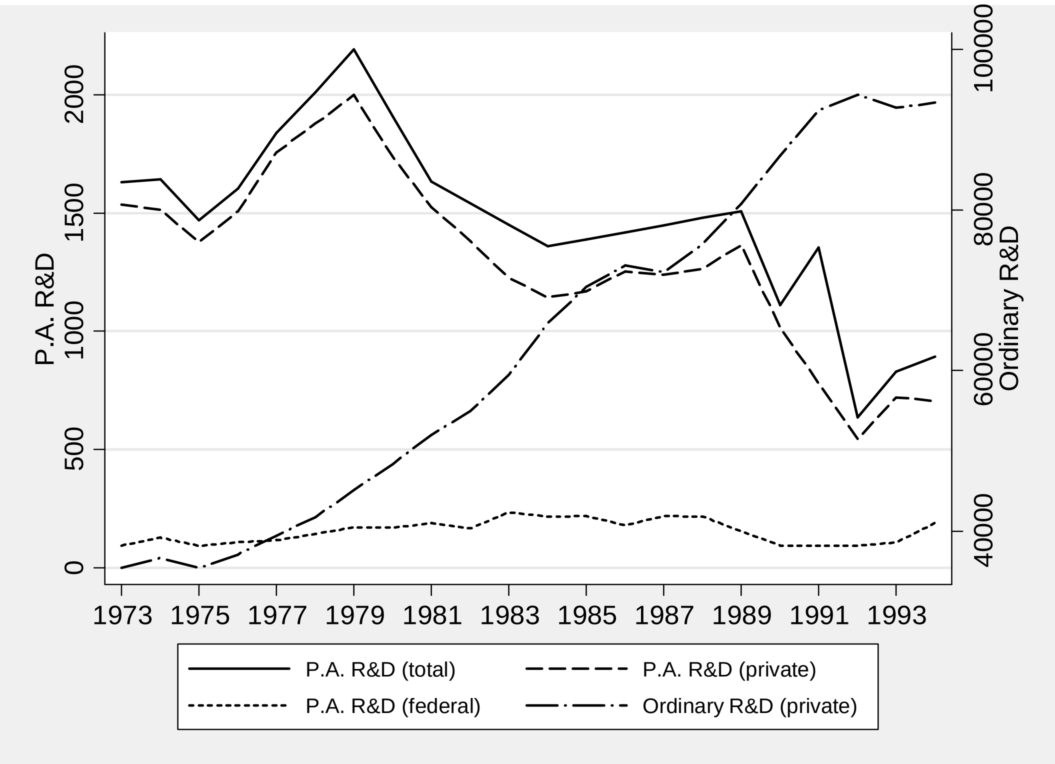
> 'If the only purpose of the R&D spending is pollution abatement, include the total expenditures on the project. If pollution abatement is only one of several purposes, report only the R&D costs associated with pollution abatement. When the separation of joint costs is not feasible, include the total R&D costs for a project if the purpose is primarily (more than 50 per cent) for pollution abatement.' (NSF 1999c: 11)

The dependent variable therefore mitigates the dual use problem by instructing respondents to report their R&D spending based on the aim that they had in undertaking the R&D. The purpose of R&D is known only by the respondent. If the respondent had pollution abatement as well as non-pollution abatement aims, then they should have reported only the part for pollution abatement. With patents by contrast it is very difficult to know with this level of precision the reason the inventor had in mind for undertaking the inventive activity that led to the patent.

This is a more specific definition of the idea of 'environmental R&D' than has been used in some prior environmental innovation studies. Brunnermeier and Cohen's (2003) dependent variable, environmental protection patents, included patents on inventions related to renewable forms of energy production as well as patents on inventions for controlling pollution. In the NSF data, R&D activity for renewable forms of energy would have been *excluded* if the purpose of the R&D was to create a new energy supply source and not to abate pollution. Horbach (2008) defined 'environmental innovation' as any firm's effort to develop a new product as long as that firm belonged to the 'environmental sector'. Horbach determined membership in the environmental sector by the firm's answer to the question: 'Does your firm offer goods or services related to the reduction of environmental impacts?' (2008: 167). Many firms could be inclined to respond to this question in the affirmative. Arimura, Hibiki and Johnstone (2007) defined environmental innovation to included R&D for 'environmental conservation' and 'environment-related' purposes, but a more precise meaning is not given. In the present study, operationalizing environmental R&D as 'pollution abatement R&D' makes it more likely that the R&D activity that is being observed in the dependent variable is a response to pollution control regulation specifically, as opposed to a response to other R&D-inducing factors, like energy prices.

When environmental R&D is defined this way a trend emerges in the dependent variable. Figure 1 shows that private pollution abatement R&D spending increased during the 1970s to a peak of about two billion (real 1992) dollars per year. Spending then gradually decreased during the 1980s before declining sharply around 1990. Federal pollution abatement R&D shows somewhat less variability. In contrast to private R&D for pollution abatement, private R&D for all other 'ordinary' purposes (private R&D spending minus that for pollution abatement) increased steadily during the same period. Pollution abatement R&D is read against the left axis and ordinary R&D against the right.

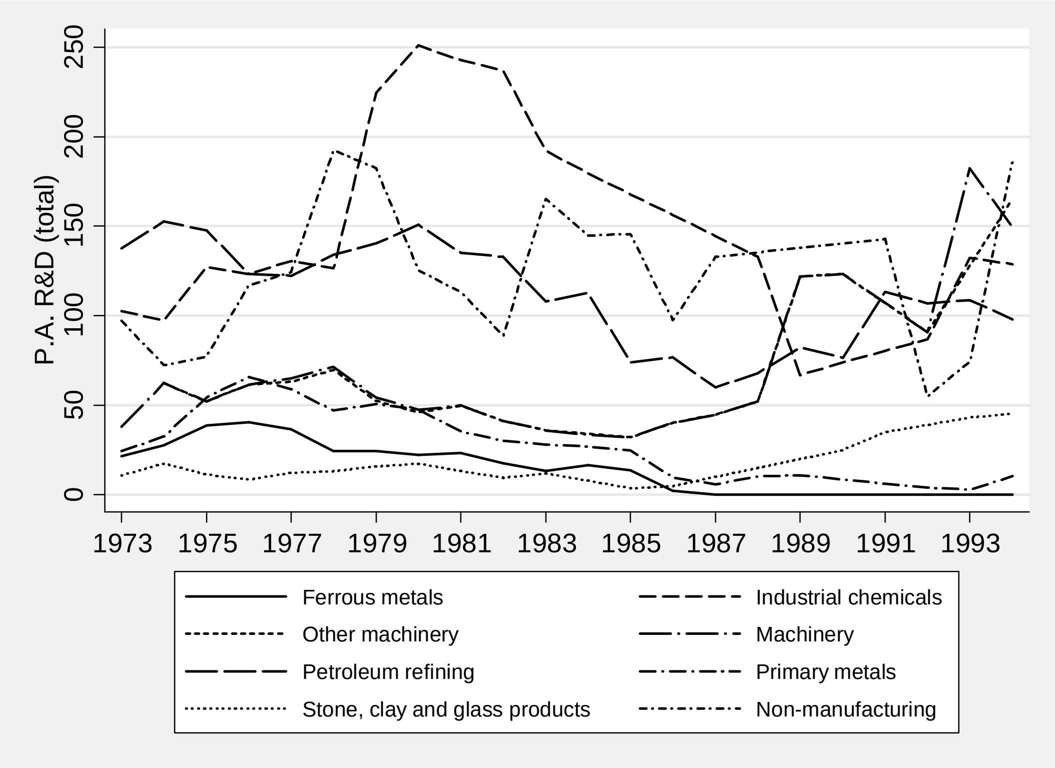
Figure 1: R&D for pollution abatement and all other ordinary purposes (millions 1992 USD)



Note: Pollution abatement R&D, read against the left axis is R&D for the purpose of eliminating the emission of pollutants to outside a firm's property or activities as through R&D aimed at prevention, treatment or recycling. Ordinary R&D is for all purposes, minus pollution abatement R&D.

Pollution abatement R&D spending can also be broken down by industry group. In Figure 2 the trends in Industrial chemicals, Petroleum refining and Primary metals broadly reflect the aggregate decline. On the other hand spending by the Machinery industry group began to increase around the late 1980s/early 1990s.

Figure 2: US pollution abatement R&D spending by industry group (millions 1992 USD)



Note: Level of pollution abatement R&D spending, by companies and the federal government combined, for selected industry group. Pollution abatement R&D includes R&D for controlling pollution emissions to any environmental medium (air, water, land, other).

The spending trend for the Machinery industry group in Figure 2 might be interpreted as follows: the transition toward more market-based forms of environmental regulation altered the early R&D spending distribution across industry groups that had formed under previous forms of regulation that did not embrace market principles. Under the earlier 'dirigiste' policy regime, industry groups were straight-jacketed into performing their own R&D however efficient or inefficient the return to that effort might have been. Under the mixed and fully market-based regimes, inefficient R&D may have uprooted from some industry groups and relocated to others where cheaper technological gains in abatement could be had for the same effort, for example upstream in the supply chain.

c. Independent variables

The degree to which the prevailing policy regime was designed around market principles is captured by *time period dummies* reflecting what are considered to be three broad policy regimes that were in place in the US between 1973 and 1994. The three periods are demarcated by the major changes that were made to automobile and power plant emission control policy through the Clean Air Act Amendments of 1979 and 1990. The detailed nature of the shift toward price signals, incentives, trading and competition during the period 1972 – 1994 was described in detail in Section 2. The degree to which air pollution policy was designed around market principles is not perfectly representative of the extent to which policy toward all pollutants was designed around market principles, but air pollution did account for the majority of conventional pollution emissions by weight in the US during the period as well as the majority of PAC spending (EPA 2001; US Department of Commerce 1993).

The 'dirigiste' policy regime is represented by a period dummy for the years 1973-1979, the 'mixed' regime by a period dummy for 1980 – 1988, and the 'market-based' regime by a period dummy for 1989-1994. The market-based regime starts in 1989 and not 1990 because Taylor et al (2004) suggest that firms probably anticipated the arrival of the 1990 Amendments somewhat through the unsuccessful 'attempts' that the US senate made to pass similar bills into law. The dirigiste regime is the base category. The coefficients on the interaction terms are interpreted as the conditioning effect of the flexible and market-based regimes relative to the rigid regime.

Other studies have used an interaction strategy under fixed effects where one of the constituent terms is a time period. Vella and Verbeek (1998) interacted the level of formal education of male wage earners with year dummies to test whether the effect of education on wages changed over time. Also using individual fixed effects, Allison (2009) tested whether children's antisocial behaviour levels changed over time by interacting the age of the individual children with year dummies. In this paper, the policy regime variable varies over time in the same way that the year dummies do in these studies, except the policy regime dummies involve longer time periods of seven, nine and six years respectively.

The second constituent term in the interaction is *total PAC expenditure*. PAC expenditure measures the level of expenditure by each industry group to abate emissions to all four environmental media: air, water, solid waste and 'other'. It includes treatment, collection/disposal, waste minimisation, source reduction and recycling. *PAC expenditure explicitly excludes pollution abatement R&D spending*

(US Department of Commerce 1993). PAC expenditure is the sum of PAC capital[1] expenditure and PAC operating[2] expenditure. PAC expenditure is lagged by three years based on Popp's (2002: 9) finding that energy technology patenting activity responded to energy price changes with a lag of about 3.7 years (2009: 9) and Jaffe and Palmer's finding that ordinary R&D spending in the US responded positively to a moving five year average of PAC operating expenditure (1997: 614).

Employment is domestic employment of R&D-performing companies measured in thousands of employees. It is used as an industry scaling variable following Jaffe and Palmer (1997) to preclude spurious correlation between PAC expenditure and pollution abatement R&D expenditure based on industry size.

Ordinary R&D spending is total industrial R&D spending net of the portion devoted to pollution abatement R&D, in millions of 1992 dollars.

Year is a linear time trend capturing all extraneous time-linked influences on pollution R&D spending. This is consistent with the way that the sources of 'autonomous' technological advance were modelled prior to the emergence of the endogenous technological change literature (Nordhaus 1994; Popp 2004; Gillingham, Newell and Pizer 2008).

Table 1 gives descriptive statistics for all variables.

Table 1: Descriptive statistics

	Definition	Obs	Mean	SD	Min	Max
P.A. R&D expenditure	Millions of 1992 dollars (*i*, *t*)	591	87.312	199.651	0	1,210
PAC expenditure	Millions of 1992 dollars (*i*, *t*)	682	887.602	1,128.093	0	6,237
Dirigiste regime	Dummy (1973 - 1979 = 1; all others 0)	726	0.318	0.466	0	1
Mixed regime	Dummy (1980 - 1988 = 1; all others 0)	726	0.409	0.492	0	1

[1] This includes end-of-line structures, production process enhancements and pollution monitoring equipment. Capital expenditure excludes capital equipment with a primary purpose other than environmental protection. It excludes equipment for improving health, safety, environmental aesthetics or employee comfort as well as the cost of manufacturing pollution abatement equipment where this is the primary business activity of the respondent.

[2] Including spending on contracted waste disposal services; payments to government for waste collection; handling, treatment or disposal of wastes created by the production process; testing and monitoring of emissions; operation and maintenance of pollution abatement equipment; fuel and power costs for operating pollution abatement equipment; compliance and environmental auditing; salaries and wages for time spent on environmental reporting requirements; the cost of developing pollution abatement operating procedures; and permits (US Department of Commerce 1993).

Market-based regime	Dummy (1989 - 1994 = 1; all others 0)	726	0.273	0.446	0	1
Employment	Thousands of employees (*i*, *t*)	609	522.025	580.842	12	6,152
Ordinary R&D spending	Millions of 1992 dollars (*i*, *t*)	591	5,095.854	8,857.036	2	89,594
Time trend	Linear time trend	726	1,983.500	6.349	1973	1994

d. Regression results

The main regression results are given in Table 2. The dependent variable is the log level of pollution abatement R&D spending by the private sector and federal government combined in each industry group-year. Specification (1) includes only PAC expenditure, the market-based regime dummy and the mixed regime dummy. The constituent variables that eventually make up the interaction are included separately. They are not interacted. This makes it possible to observe that the within-R-squared changes from .040 to .106 when they are interacted in specification (2). In specification (2) the interactions are statistically significant at the one per cent level for [PAC x market-based regime] and at the five per cent level for [PAC x mixed regime]. The signs on both interactions are negative.

Table 2: Regression results

VARIABLES	(1) lnPARD	(2) lnPARD	(3) lnPARD	(4) lnPARD
PAC expenditure (mil 1992 USD)	0.000388***	0.000796***	0.000504***	0.000504***
	(3.903)	(6.275)	(4.316)	(2.773)
Market-based regime dummy	-0.280***	0.107	0.506**	0.506**
	(-3.153)	(0.977)	(2.562)	(2.475)
Mixed regime dummy	-0.180**	-0.00673	-0.0273	-0.0273
	(-2.280)	(-0.0679)	(-0.208)	(-0.212)
PAC x market-based regime		-0.000456***	-0.000230***	-0.000230**
		(-5.622)	(-3.050)	(-2.090)
PAC x mixed regime		-0.000225***	-5.48e-05	-5.48e-05
		(-2.972)	(-0.795)	(-0.719)
Employment (thousands)			0.000463**	0.000463
			(2.252)	(1.244)
Ordinary R&D (millions 1992 USD)			4.48e-05**	4.48e-05
			(2.473)	(1.108)
Time trend			-0.0590***	-0.0590***

			(-4.302)	(-3.536)
Constant	2.561***	2.224***	119.0***	119.0***
	(25.14)	(18.53)	(4.389)	(3.606)
Observations	504	504	411	411
Within R-squared	0.040	0.106	0.234	0.234
Number of industry groups	31	31	29	29

t-statistics in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Specification (3) adds the control variables: employment, ordinary R&D spending, and the time trend. When the control variables are included the signs on the interactions remain negative and their coefficients and t-scores become smaller. Specification (4) estimates the model with robust standard errors. This reduces the significance of [PAC x market-based regime] to the five per cent level while the significance level of [PAC x mixed regime] does not change.

In specification (3) of Table 2 the positive coefficient on PAC expenditure of .000504 implies that a one unit (one million dollar) increase in PAC expenditure associates with about a .05 per cent (five one hundredths of one per cent) increase in pollution abatement R&D expenditure on average, all else being equal. This unconditional relationship between the regulatory burden and environmental innovation activity is consistent with other findings in the induced innovation literature (Hicks 1932; Brunnermeier and Cohen 2003; Jaffe and Palmer 1997; Popp 2002). Brunnermeier and Cohen found that a one million dollar increase in PAC expenditure led to an increase in environmental patenting activity of about .04 per cent.

The hypothesis test is interpreted through the coefficients on [PAC x market-based regime] and [PAC x mixed regime], which capture the relationship between PAC expenditure and pollution abatement R&D conditional on policy regime type. They give the change in the slope of the relationship between PAC expenditure and pollution abatement R&D that is attributable to the policy regime effect (Brambor, Clark and Golder 2006; Jaccard and Turrisi 2003). The coefficient on [PAC x market-based regime] in specification (3) is -.000230. This implies that the market-based regime weakened the effect of PAC on pollution abatement R&D spending by about 45.6 per cent, holding all else constant. This implies that a unit of PAC expenditure stimulated less pollution abatement R&D expenditure under the market-based regime than it did under the dirigiste regime.

The coefficient on the other interaction term [PAC * mixed regime] is negative and insignificant in the specifications with all controls in place. The mixed regime was hypothesised to weaken the effect of PAC expenditure on pollution abatement R&D spending but by a smaller amount than the market-based regime. If a one million dollar increase in PAC expenditure under the baseline dirigiste regime stimulates a .05 per cent increase in pollution abatement R&D expenditure, a one million dollar increase in PAC expenditure under the mixed regime stimulates a .045 per cent increase.

The evidence of a conditioning effect by the market-based policy regime is statistically significant but the evidence of the effect by the dirigiste regime is not.

The control variables perform as expected. The coefficient on employment is positive in line with the idea that the larger the industry group, the more pollution abatement R&D it did. The coefficient on ordinary R&D spending is positive in line with the expectation that the more R&D an industry group did overall, the more pollution abatement R&D it did. The time trend is negative. This supports the idea that knowledge and compliance techniques that did not need to be created through formal R&D may have substituted to some extent for the need to produce knowledge through formal R&D.

The main result was subjected to a range of robustness checks. In Table 3 the first specification is the baseline, which is the same as specification (3) above. Specification (2) adds a control variable for the level of federal pollution abatement R&D spending, which may have responded differently to PAC conditional on policy regime. Specification (3) tests the possibility that PAC expenditure is collinear with employment through industry group scale by replacing employment as the scaling variable with industry group sales. Specification (4) drops ordinary R&D spending on the possibility that the survey did not fully succeed in cleanly separating out R&D for pollution abatement from R&D for all other purposes.

Table 3: Robustness tests

VARIABLES	(1) lnPARD	(2) lnPARD	(3) lnPARD	(4) lnPARD	(5) lnPARD	(6) lnPARD
PAC expenditure (mil 1992 USD)	0.000504***	0.000499***	0.000559***	0.000694***	0.000687***	0.000473***
	(4.316)	(4.259)	(4.798)	(5.100)	(4.870)	(4.055)
Market-based regime dummy	0.506**	0.496**	0.581***	0.684***	0.688***	0.445**
	(2.562)	(2.505)	(2.919)	(3.019)	(2.767)	(2.215)
Mixed regime dummy	-0.0273	-0.0300	0.0419	0.236	0.275*	-0.0221
	(-0.208)	(-0.228)	(0.321)	(1.637)	(1.735)	(-0.165)
PAC x market-based regime	-0.000230***	-0.000218***	-0.000270***	-0.000389***	-0.000377***	-0.000191**
	(-3.050)	(-2.814)	(-3.568)	(-4.529)	(-4.170)	(-2.520)
PAC x mixed regime	-5.48e-05	-5.12e-05	-8.95e-05	-0.000206***	-0.000216***	-5.08e-05
	(-0.795)	(-0.740)	(-1.302)	(-2.636)	(-2.617)	(-0.735)
Ordinary R&D (mil 1992 USD)	4.48e-05**	4.68e-05**	4.13e-05**			1.59e-05
	(2.473)	(2.543)	(2.200)			(0.816)
Employment (thousands)	0.000463**	0.000442**		0.000485**	0.000504**	0.000795***
	(2.252)	(2.122)		(2.057)	(2.008)	(3.629)
Time trend	-0.0590***	-0.0594***	-0.0642***	-0.0378**	-0.0402**	-0.0526***
	(-4.302)	(-4.323)	(-4.811)	(-2.481)	(-2.413)	(-3.806)
P.A. R&D (federal)		0.00188				
		(0.637)				
Domestic net sales			1.93e-06*			
			(1.654)			
Constant	119.0***	119.9***	129.6***	76.92**	81.66**	106.4***
	(4.389)	(4.411)	(4.906)	(2.551)	(2.478)	(3.890)
Observations	411	411	409	446	394	392
Within R-squared	0.234	0.235	0.229	0.130	0.134	0.253
Number of industry groups	29	29	29	31	25	28

t-statistics in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Specification (5) confronts a potential source of weakness in the model that derives from areas of patchiness of the R&D survey data. NSF compiled the data from a random sample of 16,000 US manufacturing firms (US Department of Commerce 1993). NSF withheld values for some industry group-years because the data did not meet NSF statistical quality standards or because disclosing them might have revealed individual firm identities (NSF 1999b). (The missing values problem is apparent in Table 2 where the number of observations falls by 20 percent between specifications (2) and (3)). Specification (5) estimates the model without the Drugs and medicine (SIC 283), Communication equipment (SIC 366) and Optical, surgical, photographic and other instruments (SIC 384-387) industry groups. Specification (6) drops the Machinery industry group (SIC 35) which was observed in Figure 2 to have undergone an unusual trend perhaps because of its upstream position in the supply chain relative to heavy polluting industries. These six tests do not produce major changes in the sign, significance level or magnitude of the coefficients of interest.

4. Analysis and contributions

This paper set out to investigate whether it is realistic to expect polluters to spend large amounts of money on R&D for the specific purpose of pollution abatement under policy instruments that leave many aspects of the compliance process to firms and market forces. Nothing about this research challenges the view that market-based instruments are more efficient than rigid, so-called dirigiste instruments, or that market-based instruments are less effective at achieving pollution control goals. Rather, the paper critically examined some of the reasons given for *why* market-based instruments are thought to be more efficient with respect to innovation behaviour, and particularly the claim that their efficiency derives from the new environmental R&D spending they induce. The empirical evidence examined here gives some support to the hypothesis that the pollution abatement R&D-motivating effect of market-based instruments may be weaker than expected, at least in the experience of the United States, for the industry groups and years considered here.

One explanation for this result may be that market-based instruments allowed polluters to make greater use of pre-existing pollution control technologies as well as knowledge and technologies that they were able to acquire in informal ways, in lieu of the need to perform formal R&D themselves (Popp 2002; Griliches 1990; Evenson 1991). The knowledge and technology of fuel switching is a prominent example in air pollution control for electric power plants. This is because market-based instruments implicitly permit a wider range of compliance techniques than dirigiste policies and in so doing invite powerful market forces to search out ways to minimise the cost of compliance. R&D for the specific purpose of pollution abatement may be a casualty in that cost minimisation process, even though the ultimate end of inexpensive compliance is served. Market-based instruments may still induce abatement techniques that are 'innovative' relative to the status quo, and relative to what the regulator might have required, but there are lots of innovative techniques that involve little or no formal R&D.

The NSF data analysed here are directly relevant to the current discussion about the role of environmental R&D – or more specifically GHG abatement R&D -- in climate change mitigation. It is unusual to find a dataset measuring environmental R&D spending that covers 22 continuous years. The author is not aware of another study using environmental R&D spending data that covers this long a time period. Kemp and Pontoglio (2011) recently pointed out that a barrier to understanding the causes and effects of environmental technological change is the lack of studies that employ fixed effects on panel data covering extended time periods. This study addresses that need directly. Other studies have covered ten, 12, 12 and 20 year periods (Popp 2002; Brunnermeier and Cohen 2003; Jaffe and Palmer 1997; Popp 2002), almost all have used patent data and not all have employed fixed effects. Further, this study makes a bottom up empirical contribution a literature that has tended to be dominated by top-down theoretical modelling work.

This study also brings more precision to the way malleable but important ideas like 'environmental R&D' can and should be conceptualised and measured. The NSF questionnaire managed to overcome the 'dual use' problem in the measurement of the dependent variable. When 'environmental' R&D is defined as 'pollution abatement' R&D it emerges that real annual aggregate spending declined considerably after 1979. Studies of the causes of 'environmental innovation' more broadly defined suggest the opposite trend (Nameroff, Garant and Albert 2004; OECD 2008: 36; Hascic, Johnstone and Michel 2008). This is not the first study to observe this trend (Lanjouw and Mody 1995; Nemet and Kammen 2007; Sanyal 2007) but it is the first study to the knowledge of the author to look at the trend comparatively across industry groups; to hypothesise that increasingly market-based forms of environmental regulation are partly responsible for the decline; to formally test that hypothesis under industry fixed effects; and to suggest that compliance methods involving unoriginal forms of knowledge and technologies may have come to play a greater role.

For policymakers, these results suggest that the quest to incorporate market principles and institutions into instrument design is a good thing in its own right, and that greater environmental R&D spending may also be a good thing in its own right, but that market principles and institutions may undermine the incentives firms have to perform pollution abatement R&D. These findings also reiterate the point that the overriding objective of pollution control policy should be to create institutional structures that reduce pollution emissions cheaply (Kemp and Pontoglio 2011), not to induce innovation or R&D for its own sake.

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