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Exporting and the Environment: A New Look with Micro-Data

**by Sourafel Girma, Aoife Hanley and
Felix Tintelnot**

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Exporting and the Environment: A New Look with Micro-Data

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Abstract:

Previous aggregate studies ignore additional environmental improvements caused by intra industry reallocations to high productivity/ low pollution firms. They also fail to consider potential differences in abatement efforts by exporting status. Our estimation based on UK firm level data from 1998 to 2002 shows that exporters are 7.5 percent more likely to denote their innovation as having a ‘high’ or ‘very high’ environmental effect. Our findings also show that exporters are 17.5 percent more likely, all things equal, to report that their firm’s innovation cuts the cost of energy/ materials. Our results agree with our environment trade model which predicts that exporters amortize the fixed cost of environmental abatement over their wider output base

Keywords: Exporting, environment, innovation, heterogeneity

JEL classification: O31 - Innovation and Invention: Processes and Incentives; Q55 - Technological Innovation; Q56 - Environment and Development; Environment and Trade; Sustainability; Environmental Accounting; Environmental Equity; Population Growth

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1. Introduction

In June 2008 Environment Ministers from OECD countries have convened a series of meetings in Paris designed to confront the dual issues of a deteriorating climate and the perceived role played by trade in leading to further climate deterioration. We use the word ‘perceived’ role of trade in exacerbating climate change because as of yet, there is no consensus among trade and climate economists that trade is either good or bad for the environment.

What we do have is a set of competing theories as to the effects of trade, some of which predict markedly different outcomes. Models supporting the ‘pollution haven hypothesis’ predict a shifting of pollution to low income, developing countries. Alternatively, models supporting the ‘factor endowments hypothesis’, predict that it is capital rich developed countries which are most adversely affected by pollution because capital-intensive processes are more environmentally damaging than labour-intensive processes. Finally, models on the lines of the ‘environmental Kuznet-curve hypothesis’, predict an inverted U-shaped curve effect of industrialisation on pollution where developing countries gradually succumb to higher levels of pollution with advancing industrialisation.¹ This effect decelerates and eventually reverses as incomes in these countries rise.

There is arguably greater consensus in the empirical literature. Here recent aggregate studies have breathed some hope into the debate that trade might actually be beneficial for the environment. Most notably Levinson (2007) and Antweiler et al. (2001) have independently shown benefits to trade.

Levinson (2007)’s findings lead him to conclude that trade represents a sustainable way of protecting the environment and lead him to refute the ‘pollution havens hypothesis’. US air quality improves because trade promotes the use of superior technologies which are kinder to the environment ;

‘..if the cleanup has been the result of technology, that may well be replicable indefinitely....’ [Levinson, 2007; p.1]

Levinson (2007) and Dean and Lovely (2008) directly, and Antweiler et al (2001) indirectly conclude that trade brings in its wake technical advances which make for cleaner production. Specifically, Antweiler et al. (2001) synthesise the three types of environmental models by building a Heckscher-Ohlin type model with two factors and two final, homogeneous goods. Pollution is generated as a negative by-product from manufacturing the capital-intensive good. They augment the model by allowing for differences in international regulations on pollution abatement as well as allowing countries’ incomes and preferences to differ. Accordingly, aggregate trade patterns are predicated on differences in

¹ See for example Grossman and Krueger (1995)

factor endowments but also incomes and regulations. Their analysis decomposes trade effects into a scale ('always negative'), technique ('always positive') and composition (direction ambiguous) effect. The overall outcome of their model is that higher incomes induce populations to demand and be prepared to pay for a cleaner environment. Additionally, governments apply increasing environmental regulations to make industry pay for the clean-up: the result is a cleaner environment with greater trade and industrialisation.²

Against this backdrop of frequent public hostility towards trade as an agent for climate destruction, hostility unlikely to be tempered by a lack of consensus in the literature on the effects of trade, we believe it is time to look again at the effects of trade on the environment through the lens of individual firms. The advantage of using micro data is that existing studies have assumed that all firms behave similarly (within broadly defined sectors). Bartelsman and Doms (2000) have shown the weaknesses of concluding from aggregate studies alone when there is a lot of within-sector heterogeneity.³

We apply a novel theoretical framework which builds on Melitz's (2003) approach⁴. Exporters with their expanded sales base and differential (export and domestic market) competitive pricing strategies are better poised than their non-exporting peers to amortise fixed abatement costs. Our model shows that even if all firms had equal access to green technologies, more productive exporting firms possessing higher output and lower per unit variable costs can more easily absorb the fixed cost of abatement technology. Therefore, more productive exporting firms opt for green technologies because they can afford them. This effect is not just a one-off effect. It is sustained through a widening productivity gap between exporters and non-exporters. This is because green technologies, being invariably newer, more advanced technologies, often involve the replacement of obsolete or poorly performing equipment with state of the art equipment. This additional effect means that the introduction of green technology by exporters can bring about further productivity improvements in addition to combating environmental fallout.

Our paper is the first, to our knowledge to use a panel of firm level data to examine the reported impact of innovation on the environment for a sample of UK exporters and non-exporters. Specifically, we look

² Dean and Lovely (2008) conclude more in favour of the pollution havens hypothesis because they infer that China's clean-up is the result of shunting dirtier processes elsewhere (composition effect from fragmentation).

³ The latter study looks at productivity

⁴ For a more comprehensive discussion of our model see Tintelnot (2008)

at environmental abatement and the reduction of expenditure on energy and material inputs.⁵ Using data from the UK Community Innovation Survey and Companies Registration Database from 1996 to 2004, we find that innovation has become more important as a tool for both environmental measures. Specifically, we find that exporters profess a significantly higher impact of the application of innovation to pollution abatement and preventing materials wastage.

We find that even when controlling for heterogeneity among firms (productivity differences, narrowly defined sectoral FDI, size and skills), that exporters consistently rate higher in reporting the effect of their use of innovative technologies on the environment. They also rate higher in reported energy cost cuts achieved through using innovation. Our estimations generated on UK firm level data from 1998 to 2002 show that exporters are 7.5 percent more likely to denote their innovation as having a ‘high’ or ‘very high’ environmental effect. Our findings also show that exporters are 17.5 percent more likely, all things equal, to report that their ‘firm’s innovation cuts the cost of energy/ materials’.

Interestingly, when we evaluate the effects of exporting and productivity jointly on the propensity to carry out environmental abatement, we find that at higher productivity levels, exporting induces an even higher propensity to engage in environmental clean-up. Specifically, this effect is circa 0.5 percent for exporters in the highest productivity quartile.

Our paper is structured in the following way. We present our model in Section 2. Section 3 describes the empirical model used and Section 3 discusses the construction of the data set and its key features. . Section 5 discusses the empirical findings and the final section concludes.

2. Our model

In this part of the paper we create a theoretical framework to analyze how the firm’s decision to invest in pollution abatement is expected to change as we move from a closed to an open economy. We also look at how abatement efforts differ between exporting and pure domestic firms. Specifically, we build on the trade model with heterogeneous firms in Melitz (2003).⁶

⁵ The questions asked of respondents are ‘Improved environmental impact’ and ‘Reduced materials and/or energy per produced unit’ respectively

⁶ The industry’s equilibrium is described further in Tintelnot (2008).

Abatement efforts in the closed economy

Our benchmark for assessing the environmental effects from trade is an isolated, closed-economy. We assume that each firm within the industry differs by its productivity parameter ϕ and produces a particular type of product. Pollution, denoted by z , arises proportional to a firm's output. Pollution is costly to the firm (e.g. through carbon emission certificates in Europe). These costs are denoted by the tax rate, τ . The amount of pollutant released into the environment depends on a firm's abatement technology function, $a(\theta)$, where θ indicates the abatement effort.⁷ Labour represents the only factor of production and the wage rate is set equal to one. Besides abatement technology expenditures, $c\theta$, a firm incurs fixed costs of production, f . A firm's total cost function is determined as

$$(1) \text{ TC: } f + \left[\frac{1}{\phi} + \tau z a(\theta) \right] q(\phi, \theta) + c\theta$$

Consumer's demand for each type of variety is described in (2), where βI denotes the income spend on goods from the polluting sector and P_s represents the sector's price index, analogous to Dixit and Stiglitz (1977).

$$(2) q(\phi) = \frac{\beta I}{P_s} \left[\frac{p(\phi)}{P_s} \right]^{-\sigma}$$

$$(3) P_s = \left[\int p(\phi)^{1-\sigma} d\phi \right]^{\frac{1}{1-\sigma}}$$

A firm maximizes its profit function described by (4) with respect to its price, p , and abatement effort, θ .

$$(4) \pi_{p,\theta} = \beta I \left[\frac{p}{P_s} \right]^{1-\sigma} - \left[\frac{1}{\phi} + z\tau a(\theta) \right] \beta I \left[\frac{p}{P_s} \right]^{-\sigma} - f - c\theta$$

⁷ We assume that pollution per unit of output is declining in θ and $a(\theta)$ is a convex function for positive values of θ . This means $0 < a(\theta) \leq 1$, $a'(\theta) < 0$, $a''(\theta) > 0$.

In general a higher productivity parameter, ϕ , will result in a choice of better abatement technology (higher θ).⁸ To solve the model explicitly, we specify the abatement technology, $a(\theta)$, as $1/\theta$. Additionally we set the elasticity of substitution to be equal to two.

Then maximization of profits from (4) yields,

$$(5) \theta = \phi k_1, \text{ where } k_1 = \frac{\sqrt{\beta IP_s z \tau} - 2z\tau\sqrt{c}}{2\sqrt{c}} \quad ,$$

and

$$(6) p = \frac{1}{2\phi} k_2, \text{ where } k_2 = \frac{\beta IP_s}{\beta IP_s - 2\sqrt{cz\tau\beta IP_s}} \quad .^{10}$$

A more productive firm charges a lower price and therefore has larger output. Consequently, it can spend more on abatement technology than a less productive firm, since it can allocate these fixed costs to more units of output. In other words, a more productive firm can more readily amortise the fixed cost of investing in abatement technology because its more competitive pricing helps ensure a wider customer base over which to spread this fixed cost.

Abatement efforts in the open economy

As in Melitz (2003), let us consider the hypothetical case of an identical country as trading partner. Variable transport costs t arise, which are modelled in the standard Iceberg-transport cost setup. Additionally, exporting firms have to cover the fixed cost of export market entry f_{ex} .¹¹ For a firm entering the export market, the joint profit from domestic and export markets has to be higher than the profit

⁸ See appendix

⁹ From the square root of a quadratic function there is also a negative solution for θ . θ is restricted to positive values and it can be shown that the profit function in (8) is indeed maximized for the p^* and θ^* from equations (9) and (10).

¹⁰ Both p and θ are positive as long as $\frac{\beta_1 IP}{4c} > \tau z$.

¹¹ This one time entry cost can be transformed into per period fix costs of exporting, f_x .

arising from serving the domestic market alone. The optimal domestic and foreign prices and the level of pollution abatement differ according to export status.

Formally, a firm chooses to export, if

$$(7) \pi_{D+X} > \pi_D.$$

Although the relation is not formally derived in this paper, we assume fixed and variable export costs to be such that not all firms will find it profitable to export. The profit function of an exporting firm looks like:

$$(8) \pi_{D+X} = \beta I \left[\frac{P_d}{P_S} \right]^{1-\sigma} - \left[\frac{1}{\phi} + z\tau a(\theta) \right] \frac{\beta I}{P_S} \left[\frac{P_d}{P_S} \right]^{-\sigma} + \beta I \left[\frac{P_x}{P_S} \right]^{1-\sigma} - \left[\frac{1}{\phi} + z\tau a(\theta) \right] t \frac{\beta I}{P_S} \left[\frac{P_x}{P_S} \right]^{-\sigma} - f - c\theta - f_x$$

An exporting firm faces three choice variables: Domestic and foreign price, and the level of abatement technology. The optimal levels of these variables are then (again considering $\sigma = 2$ and $a(\theta) = 1/\theta$, for the derivation please see Appendices 1 and 2):

$$(9) \theta = \frac{\phi(\sqrt{cz\tau\beta I P_S(1+t)} - 2czt\tau)}{2ct}$$

$$(10) p_{de} = \frac{2\sqrt{cz\tau\beta I P_S(1+t)}}{\phi\sqrt{cz\tau\beta I P_S(1+t)} - 2czt\tau}$$

$$(11) p_x = tp_{de}.$$

For a non-exporting firm, the pricing and abatement decisions look like equations (5) and (6), with the only difference being that the price index P is lower in the open economy. As in the standard Melitz-model, a firm confined to serving the domestic market alone under the open economy, faces an output loss in comparison with its sales under autarky. Here, this output loss arises through the non-exporting firms being forced to charge a higher price under the open economy. This higher price is necessitated because it reflects the firm's now diminished ability to recoup its fixed costs of abatement technology

over a shrinking output base. Conversely, an exporting firm, charges a lower price in its domestic market compared to its non-exporting counterpart. Notwithstanding the lower price charged to domestic customers by exporters (compared to the price charged by non-exporters), the export price charged on export markets is higher than the price charged on the domestic market. This price premium reflects the additional transport costs incurred by exporters.

Not only does trade openness lead to a reallocation of market shares to less pollution-intensive firms, it makes low pollution firms spend even greater amounts on pollution abatement, an action which further improve their pollution efficiency. Purely domestic operating firms instead, cut costs for abatement technology, since their total output declines. This feature of trade openness further widens the gap between exporters and non-exporters.

$$(12) \quad \begin{matrix} \theta_{OE}(\phi) > \theta_{CE}(\phi) \\ \theta_{OE}(\phi) < \theta_{CE}(\phi) \end{matrix}, \text{ if } \begin{matrix} \phi > \phi_x^* \\ \phi^* < \phi < \phi_x^* \end{matrix} \quad 12$$

The changes we have just discussed in pollution abatement efforts as we move from a closed to an open economy, and the associated differences arising between domestic and exporting firms' abatement technology efforts, are displayed by Figure 1.

The curve displays abatement technology efforts along the productivity continuum (in the open economy). The curve also guides our predictions for this paper for our regressions which follow. Overall, the relationship between firms' abatement technology effort and productivity is expected to be positive. The kink in the curve for the open-economy scenario, informs our prediction that exporters spend comparatively more on pollution abatement than their non-exporting peers. The theory therefore predicts that exporters will exhibit higher pollution abatement efforts, all things equal. It follows that the predicted sign on the exporting coefficient should be positive. Another feature of the model which we can use to guide our empirical model which follows in the paper is the steeper slope of the abatement effort function for productivity levels higher than ϕ_x^* . This steeper slope underpins an important interactive effect for productivity and exporting status. Accordingly, we expect a positive sign for the productivity/ exporting interaction.

¹² ϕ_x^* denotes the threshold productivity level for exports. Only firms with a productivity level higher ϕ_x^* export. ϕ^* denotes the threshold productivity level in the closed economy. Firms with a lower productivity level exit immediately.

3. Empirical Methodology

We set out to show whether, using unique firm level data, exporters demonstrate higher environmental abatement effort than non-exporters. Specifically, we look at whether exporters use technology that 1) registers a high environmental impact and 2) leads to energy/ inputs cost cuts. This reasoning is in line with our model outlined above where we expect a different intercept term for exporters vis-à-vis non-exporters, for the effect of productivity on environmental abatement. Accordingly, we model the environmental innovativeness of exporters vs. non-exporters, having controlled for productivity. We also control for additional covariates causing heterogeneity in firm's responses, as has been proposed in similar analyses (Dean and Lovely, 2008; Eskeland and Harrison, 2003; Dasgupta et al., 1998; Cole et al, 2005).

$$\text{Prob}(\text{Environmental abatement} = 1: 4)_{it} = \beta_i (\text{exporter})_{it} + \beta_2(\text{productivity})_{it} + \beta_3(\text{skills})_{jt} + \beta_3(\text{size})_{it} + \beta_4(\text{FDI})_{jt} + \beta_5(\text{survey wave})_i$$

Our measure of environmental abatement is important. It is a 4-point ordinal response to two questions with answers ranging from not at all important to very important. The questions elicit from respondents whether their innovation led to 1) “Improved environmental impact or health and safety aspects” and 2) “Reduced materials and/or energy per produced unit”. Although, these measures are self-reported, a point in their favour is that they are direct and firm-specific. Additionally, similar firm-specific, self-reported measures have been successfully used by others using micro data in different contexts.¹³ The second question arguably eschews any problems with response bias. It ascertains whether innovation is used to help save energy/materials. Answers are also scaled on a 4-point scale.

We use an ordered probit model which allows for ordinal outcomes.¹⁴ We ensured that standard errors were robust to heteroskedasticity and within-establishment serial correlation.

Export status is a dummy variable denoting whether a firm exports. We also include sales per worker (productivity) at the firm level. Our model provides the intuition for this: abatement is increasing in productivity (the function slopes upward). Moreover, we do not want to infer any effects to exporting

¹³ e.g. Criscuolo and Haskel (2003) who look at the self-reported introduction of new or advanced products/processes and Belderbos et al., (2004) who examine inter-firm cooperation

¹⁴ We are unable to calculate a conditional fixed-effects model, as it is impossible to separate the fixed effects from the overall likelihood.

without first netting out productivity differences. Finally, the inclusion of productivity interactions allows us to explore the idea advanced in our model that there are important productivity interactions for exporting firms on environmental abatement.

Other work on environmental abatement has included additional covariates. Skills, recently included as a covariate in Dean and Lovely (2008), we denote as the average percentage of university educated employees in the firm's 4-digit industry.¹⁵ Size, which has been used in several studies so far, is formulated as number of employees (Dasgupta et al., 1998; Cole et al, 2005). FDI is a narrowly defined industry variable from the FAME database of UK registered firms, describing the presence of foreign owned firms in the 4-digit sector.¹⁶ We include FDI on the basis that foreign firms are significantly more energy efficient and use cleaner types of energy (Eskeland and Harrison, 2003; Dean and Lovely, 2008).¹⁷

Finally, we needed to include a CIS (Community Innovation Survey) wave indicator to denote the separate survey waves. We discuss the construction of the panel in the section which follows.

4. Database construction and sample characteristics

We use data from several sources. Our main firm-level information on environmental abatement and innovation induced energy savings is drawn from the UK Community Innovation Survey. We also draw industry level data from the Bureau Van Dijk database of UK firms. Finally, we include information on the importing behaviour of UK owned firms (used in the subsequent instrumental variables analysis) from the Republic of Ireland. For this we use information from the Annual Business Survey of Economic Impact (ABSEI), covering the period from 2000 until 2006 and the Irish Economy Expenditure (IEE) Survey data, also administered by Forfás, covering the period 1983 to 2002.¹⁸ These two datasets contain surveys of plants in Irish manufacturing and services industries with at least 10 employees. The Irish data is comprehensive with response rates for the ABSEI standing at around 55 to 60 percent of the targeted population per year.

¹⁵ Dean and Lovely (2008) alternatively formulate skills as the ratio of skilled to unskilled workers in an industry.

¹⁶ The standard UK Office for National Statistics criteria for foreign ownership is used: a majority shareholding or foreign registration.

¹⁷ Some summary statistics for key covariates are contained in Appendix 4

¹⁸ A plant, once it is included in the survey, is generally still surveyed even if its employment level falls below the 10 employee cut-off point

The CIS survey is administered every alternate year to a representative sample of UK businesses drawn from the registrations database. A major advance in research years of the survey which we exploit for our work, is that for the first time, firms in the third survey (CIS3) and fourth survey respectively (CIS4), could be merged into an acceptable panel.¹⁹ Table 1 shows the breakdown of our panel when matching the two consecutive cross-sections.

The first cross-section we use comprises the period 1998 to 2000 and the second cross-section represents the period 2002 to 2004. Altogether we created a panel of around 950 firms for the period covering 1998 to 2004. Several things are clear from the matching process. First, there was a relatively high attrition in the sample between the two survey waves. Just over 13 percent of the firms could be matched from the original survey. We do not know to what extent firms were lost to the panel due to non-response or the possibility that some many of the firms sampled in CIS3 had ceased to trade/ trade under their former name by the time they were sampled in CIS4. Roughly similar firms were sampled in both waves of the CIS. A perusal of the turnover statistics for the years contained within the two surveys shows that firm size in the latter wave, appears slightly smaller (lower median turnover and slightly higher variance of turnover).

Overall CIS firms were larger than firms in the more well known FAME database of UK firms taken from the population (Table 2) where the median CIS firm had circa 280 employees in any survey year and the corresponding number for the FAME data stood at around 60 employees.

Mercer (2004) in her description of the CIS, reports how the VAT registrations database is used to identify the sample frame for the CIS. The VAT registrations database for the UK, referred to as the Interdepartmental Business Register (IDBR) and administered by the Office for National Statistics provides the most exhaustive listing of UK firms of all sizes, sector and establishment type. Firms in 12 broad industrial sectors with at least 10 employees are identified and the survey administered to the sample frame which was chosen to be statistically representative of firms in the population. The response rate was approximately 43 percent for the CIS3 and 58 percent for CIS4.

Given that exporting status represents a key variable in our analysis, we note which sectors are most export intensive. Accordingly in Table 3, we counted the share of exporters in any sector for the final year of the survey (2004) and from this calculated the percent of exporters active in each 2-digit sector.

¹⁹ Other researchers who have constructed panels from these survey cross-sections are Criscuolo and Haskel (2003) and Belderbos et al. (2004) for the UK and Netherlands respectively.

Unsurprisingly, the sectors manifesting the highest rates of exporting activity are the traded sectors such as manufacturing of computers, radio equipment, textiles and petroleum products. At the bottom of the list, feature the non-traded sectors such as pensions and insurance products which are primarily geared towards the home market.

We repeated this exercise for the number of firms in each sector in 2004 who stated that technologies they had introduced had a 'high' or 'very high' impact on the environment (Table 4). Here we see a slightly different pattern emerging, with industries such as tanning and mining showing very high in the rankings. These activities have the potential to cause severe environmental degradation. The limitation of these tables is that they summarise the information in a uni-dimensional way and are not that revealing except to confirm that our measures of exporting and environmental abatement are behaving as expected. Much more interesting would be the question of how individual firms in each sector exhibit their own singular abatement propensities, having netted out the influence of important inter-firm differences such as size and productivity.²⁰ For this we turn to the analysis section.

5. Empirical findings

It is worth recalling briefly that the theory outlined in section 2 predicts that environmental abatement effort is increasing in a firm's productivity. An additional factor reinforcing the effect of productivity on environmental abatement is the higher efficiency of new, cutting edge equipment which is also by default likely to be environmentally friendly. The theory further predicts that exporting firms, expend higher effort in cleaning up their production than non-exporters because of their increased ability to amortise the fixed cost of abatement expenditure over their increased sales (domestic and export) volume.

Table 5 shows the impact of innovation on the environment based on a series of ordered probit models, with 4-categories as possible outcomes; innovation in my firm has 'no effect', 'some effect', a 'high effect', and a 'very high' effect, respectively on the environment.

Model, (1) reports the results for the exporting dummy and controls only. The exporting dummy is significantly positive at the 1 percent level and the covariates carry the expected signs. In model (2), we repeat the exercise but on this occasion, we include logged productivity as an additional covariate. The inclusion of logged productivity is based on the intuition from our model that heterogeneous productivity accounts for much of the variation a firm's capacity to undertake environmental abatement.

²⁰ Appendix 4a and 2b contain descriptive statistics for these controlling variables

Disappointingly, logged productivity, although carrying a positive sign as expected, is insignificant. The theory however posits that the productivity / abatement capacity relationship is possibly concave (for an open economy). Accordingly, in model (3) we categorise the continuous variable into discrete quartiles and include the upper three categories, assigning the first quartile to the base category. We now see a different picture emerging. Both the uppermost productivity categories carry significant and positive signs. Therefore, at least for firms in the uppermost ranges of the productivity distribution, the innovation used by firms reportedly reduces environmental degradation.

Finally, we test the theoretical prediction that the productivity-abatement relationship depends on whether a firm is an exporter or not. We find that both the upper two productivity/ exporting interactions are significantly positive and systematically different from the base category. This shows that productivity mediates the relationship between exporters and environmental abatement. The most productive exporters are significantly more likely to be able to invest in green technologies as they can spread the fixed cost of the investment over their expanded overall output.

We can observe the same effect visually in Figure 2 which is constructed from the estimates obtained earlier in the ordered probits (Table 5). In many ways, Figure 2 is analogous to the theoretical Figure 1 which was constructed from the theory model. On the x-axis we show productivity increases. On the y-axis we show the propensity of respondents to rate their technology as “having no impact” on the environment. The green and red lines chart the predicted probabilities for exporters and non-exporters respectively. It is clear that overall, higher productivity leads to a lower probability that any respondent will rate their technology as “having no impact” on the environment. Productivity, in this sense, is associated with the deployment of environment enhancing innovation. It is also true that exporters, for any given level of productivity, consistently lie beneath non-exporters. Another way of putting this is that exporters are more likely, all things equal and for any given level of productivity, to implement environment enhancing innovation.

We now turn to how the estimated models predict that respondents state that their technology “has a high impact” on the environment. Figure 3 shows the average predicted probability for each quartile of the productivity distribution as generated by the ordered probit. This time the curves relating to exporters and non-exporters slope up, consistent with the idea that as productivity increases, firms are more likely to state that their technology “has a high impact” on the environment. This is most likely due to the inextricable link between new, cutting edge technologies which have the advantage of being both

efficiency inducing (Tintelnot, 2008)) as well as being environmentally friendly and the lower unit costs for abatement technology for exporting and more productive firms through higher output.

However, we also observe an additional effect which is the mirror image of what we witnessed earlier in Figure 2 – this time the green line, denoting exporters, lies above the red line denoting non-exporters for all levels of productivity. Therefore, exporters are more likely to say, all things equal, including productivity differences, that their technology has a “high impact” on the environment.

As a robustness check, we run the same ordered probits for our alternative measure of environmental abatement, that a firm’s innovation “cuts energy/materials costs” (Table 6). Now a real difference arises in our results when testing our hypotheses that exporting induces environmental abatement. The direct effect of exporting on the response variable is evident in all estimated models. What is missing is the indirect effect on the response variable which is transmitted through productivity. In model (4) we see that exporters are always more likely to note that their innovation helps to reduce the cost of materials and energy. However, no effect is noted for productivity on the response variable (model 3) nor are more productive exporters more likely to register an impact of innovation in cutting energy and materials costs.

This lack of an interaction effect is also clear in the accompanying figures (Figure 4 and Figure 5) which have been derived from these estimations. Unlike their predecessors, these graphs are relatively flat, suggesting that variation in the response variable is relatively insensitive to changes in productivity.

Marginal effects

Is the effect of exporting on the probability that a firm answers that its innovation has a “very high” effect on the environment, of substantial importance? In order to answer this question we need to calculate the marginal impact of exporting on the response variable. Table 7 notes our calculated marginal effects for the four categories of the response variable from ‘no effect ($y = 0$)’, ‘some effect ($y = 1$)’, ‘high effect ($y = 2$)’ and ‘very high effect ($y = 3$)’. The marginal effects calculate the change in the probability that the response falls into the category as a function of the explanatory variables. Because we have logged the continuous variables such as productivity, the marginal effect can be readily interpreted as a percentage change. For the discrete variables, values denote the percentage change in the individual categories of the ordered probit induced by the dummy variable switching to 1.

Looking at the exporter dummy, we see that as we progress to ever higher categories of the response variable, the impact of firm's innovation on the environment, the probabilities change from a 7.6 percent reduced probability that that innovation has 'no impact' to a 3.5 percent increased probability that a firm's innovation has a 'very high' impact. These effects induced by switching the exporter dummy to 1, are all significant.

We see that the effect of switching from the lowest productivity quartile to the third quartile induces a percentage change in the probability that a firm registers that its environmental impact from the technology it used is 'very high ($y = 3$)', is 3.7 percent. This is similar in magnitude to the percentage change induced by switching from the base productivity category to the highest productivity category (3.8 percent). Taken together, exporters are 7.5 percent more likely to denote their innovation as having a 'high' or 'very high' environmental effect.

We now look at the economic significance of exporting jointly with productivity. The final column of Table 7 reports our results if we change the base category (non exporters) to denote exporters for each of the other covariates including the productivity quartiles. Now the probability that respondents in the second and highest productivity category denote their innovation as exerting a 'very high' environmental effect, increases by about 0.5 percent (from the probability noted for non-exporters).

Table 8 reports the marginal effects for the alternative measure of environmental abatement, 'firm's innovation cuts the cost of energy/ materials'. Here we find substantial differences in the probability that exporting firms categorise their innovation as exerting a 'high' or 'very high' impact. Together these probabilities sum to a 17.5 percent probability differential (9 plus 8.5 percent respectively for 'high' and 'very high') over non-exporters. There is no evidence of differential productivity effects however. Nor do we see any productivity/ exporter interactive effects from the final column.

Robustness analysis: environmental abatement with endogenous exporting

Our model, which is based on similar assumptions to Melitz (2003), represents a firm's export decision as a choice variable: domestic non-exporters can decide whether or not to exploit the cost advantages that would arise to them from increased output to enter export markets. Accordingly, we need to allow for the possible endogeneity of the exporting decision. It is difficult to find appropriate instruments within the panel of firms because most measures of the exporting decision (skills or technology based) are similarly drivers of environmental abatement. Therefore, we have to look outside our data for a truly exogenous instrument. We find one such potential instrument in the Irish data. This instrument

represents the industry average/median ratio of internationally outsourced inputs to locally (Irish) procured inputs imported by UK owned firms in the Republic of Ireland. This is an intuitively appealing instrumental variable because it partially explains the degree of connectiveness between UK firms operating on mainland Britain and their peers operating in an important FDI host economy for UK firms, namely Ireland. The rationale being that many of these inputs are sourced in the UK as the UK is geographic proximate to Ireland. A further basis for supporting this instrument is more simply the issue of global engagement: higher dependency of UK firms functioning on external markets helps us to highlight those sectors of UK economic activity for which global engagement (e.g. exporting) is most attractive. Although this instrument is intuitively appealing, it must be also empirically validated through standard tests of instrument validity, exogeneity and relevance.

To our knowledge, instrumental variables estimators for ordinal choice models are not available in the literature. Accordingly we estimate the endogenous exporting model using standard instrumental variables estimation techniques.

Table 9 reports the estimates. Reassuringly, the instruments validity and relevance tests suggest the appropriateness of the instrumental variable candidates, and the estimates suggest that productivity is still highly correlated with environmental abatement at the higher levels (4th quartile). On this basis we can conclude that exporting status affects environmental abatement, even taking on board possible endogeneity of the exporting decision.

The results for the effect of innovation on the cutting of energy costs for exporters reported in columns 3 and 4 also confirm our earlier findings.

Robustness analysis: Cross-section results for separate CIS waves

To allow for variation in responses over the two consecutive survey waves, we reestimate the main probits for each survey wave. Table 10 notes the impact of exporting status on our two response variables for each survey cross-section. The coefficient for exporting is consistently positive for each measure across the individual surveys, albeit insignificant in the second survey for the environmental abatement measure. Higher productivity levels are, in most cases, associated with higher environmental abatement and costs reduction.

The variation in responses across the survey waves may point to diminishing usefulness our exporting measure as a way of capturing augmented production. For example, the increased usage of internet sales

over the period, with implications for how exporting is reported, or the possibility of increased use of transfer pricing may blur the perceived impact of exporting on environmental abatement and cost reduction. There is also the possibility of systematic survey bias. In the absence of more complete information, these possibilities remain conjectures. Nevertheless, we take reassurance from the continued positive sign exhibited by the exporting status variable, notwithstanding the above mentioned qualifiers.

6. Conclusion

Following Tintelnot (2008) who augments Melitz's (2003) environment trade model to account for exporters, our theoretical model predicts a positive relationship between firms' abatement technology effort and productivity. Our model also postulates that exporters (especially high productivity ones) invest more in pollution abatement than their non-exporting peers.

Our estimations generated on UK firm level data from 1998 to 2002 show that exporters are 7.5 percent more likely to denote their innovation as having a 'high' or 'very high' environmental effect. Our findings also show that exporters are 17.5 percent more likely, all things equal, to report that their firm's innovation cuts the cost of energy/ materials.

Our results are in line with the theory that exporters amortize the fixed cost of environmental abatement over their wider output base. Productivity interactions further underpin our finding that the most productive exporters show the highest propensity for environmental abatement.

What implications do our findings have for current policy debates on trade? Exporting is not damaging to the environment: quite the contrary. We have shown that trade is an important mechanism to make superior, cutting edge, environmental abatement technology more affordable. Open economies help create the right conditions for firms to upgrade their environmental abatement technology.

Table 1 Creating the Innovation Panel of UK firms

<i>Unmatched firms from cleaned sample:</i>				
CIS4: 2002-2004	15,486			
CIS3: 1998-2000	7,213			
<i>Matched firms from both waves:</i>				
Number of firms	959			
% of firms in CIS3 matched with CIS4	13.3			
<i>Distribution of turnover:</i>				
	N	mean	sd	median
1998 (from CIS3)	7,606	27,187	213,039	2,223
2000 (from CIS3)	7,931	35,211	389,883	2,597
2002 (from CIS4)	16,433	34,105	335,313	1,600
2004 (from CIS4)	16,437	39,816	439,953	2,000

Table 2 Comparison of Employment Size from FAME and CIS data

year	FAME database					Community Innovation Database (CIS)			
	mean	sd	p50	N		mean	sd	p50	N
1998	311	2,061	59	22,995	CIS3	488	893	276	760
2000	305	2,144	60	26,908					
2002	304	2,488	58	30,934	CIS4	504	1,111	284	769
2004	285	2,416	56	32,706					
						496	1008	282	1,529

Notes

FAME is a database of firms in the UK economy administered by Bureau van Dijk

Table 3 Sectors with the highest percentage of exporters


SIC92	Description	Percent exporters
17	MANUFACTURE OF TEXTILES	100%
23	MANUFACTURE OF COKE, REFINED PETROLEUM PRODUCTS AND NUCLEAR FUEL	100%
27	MANUFACTURE OF BASIC METALS	100%
30	MANUFACTURE OF OFFICE MACHINERY AND COMPUTERS	100%
62	AIR TRANSPORT	100%
32	MANUFACTURE OF RADIO, TELEVISION AND COMMUNICATION EQUIPMENT	96%
24	MANUFACTURE OF CHEMICALS AND CHEMICAL PRODUCTS	95%
		
41	COLLECTION, PURIFICATION AND DISTRIBUTION OF WATER	25%
65	FINANCIAL INTERMEDIATION, EXCEPT INSURANCE AND PENSION FUNDING	23%
40	ELECTRICITY, GAS, STEAM AND HOT WATER SUPPLY	20%
45	CONSTRUCTION	11%
10	MINING OF COAL AND LIGNITE; EXTRACTION OF PEAT	0%
19	TANNING AND DRESSING OF LEATHER & MANUFACTURES	0%
61	WATER TRANSPORT	0%
66	INSURANCE AND PENSION FUNDING, EXCEPT COMPULSORY SOCIAL SECURITY	0%

Table 4 Sectors self-reporting highest impact of environmental innovation


SIC92	Description	
19	TANNING AND DRESSING OF LEATHER & MANUFACTURES	100%
10	MINING OF COAL AND LIGNITE; EXTRACTION OF PEAT	67%
40	ELECTRICITY, GAS, STEAM AND HOT WATER SUPPLY	60%
20	MANUFACTURE OF WOOD AND PRODUCTS OF WOOD AND CORK	57%
71	RENTING OF MACHINERY AND EQUIPMENT WITHOUT OPERATOR AND OF PERSONAL AND HOUSEHOLD GOODS	57%
73	RESEARCH AND DEVELOPMENT	55%
23	MANUFACTURE OF COKE, REFINED PETROLEUM PRODUCTS AND NUCLEAR FUEL	50%
		
11	EXTRACTION OF CRUDE PETROLEUM AND NATURAL GAS & Rel. SERVICE ACTIVITIES	11%
67	ACTIVITIES AUXILIARY TO FINANCIAL INTERMEDIATION	9%
72	COMPUTER AND RELATED ACTIVITIES	9%
65	FINANCIAL INTERMEDIATION, EXCEPT INSURANCE AND PENSION FUNDING	8%
61	WATER TRANSPORT	0%
62	AIR TRANSPORT	0%
66	INSURANCE AND PENSION FUNDING, EXCEPT COMPULSORY SOCIAL SECURITY	0%

Table 5 Impact of Innovation on Environmental Abatement

	Ordered probit	Ordered probit	Ordered probit	Ordered probit
	(1)	(2)	(3)	(4)
Firm is an exporter	0.195 (2.81)***	0.197 (2.81)***	0.194 (2.76)***	0.054 (0.56)
FDI within 4-digit sector	0.329 (1.91)*	0.299 (1.72)*	0.282 (1.63)	0.285 (1.64)
Mean sectoral proportion of science graduates	0.007 (1.86)*	0.007 (1.89)*	0.007 (1.91)*	0.007 (1.91)*
Logged employment size	0.100 (4.04)***	0.097 (3.88)***	0.092 (3.63)***	0.091 (3.62)***
Logged productivity		0.058 (1.63)		
¹ Logged productivity 2 nd quartile			0.111 (1.29)	
¹ Logged productivity 3 rd quartile			0.189 (2.19)**	
¹ Logged productivity 4 th quartile			0.191 (2.11)**	
Exporter * prod. interaction 2 nd qtile.				0.146 (1.36)
Exporter * prod. interaction 3 rd qtile.				0.220 (2.12)**
Exporter * prod. interaction 4 th qtile.				0.222 (2.00)**
Later survey	0.638 (11.61)***	0.623 (11.24)***	0.616 (11.08)***	0.619 (11.09)***
Observations	2856	2832	2832	2832
Firms	734	732	732	732
LR χ^2	171.6	171.05	174.8	
Prob > χ^2	0.000	0.000	0.000	

Notes:

Absolute value of z statistics in parentheses; Standard errors clustered on ID

* significant at 10%; ** significant at 5%; *** significant at 1%

¹ Baseline is first productivity quartile

Table 6 Impact of Innovation in Reducing Energy & Materials Costs

	(1)	(2)	(3)	(4)
	Ordered probit	Ordered probit	Ordered probit	Ordered probit
Firm is an exporter	0.455 (6.41) ^{***}	0.451 (6.32) ^{***}	0.440 (6.11) ^{***}	0.448 (4.58) ^{***}
FDI within 4-digit sector	0.572 (3.29) ^{***}	0.575 (3.29) ^{***}	0.581 (3.31) ^{***}	0.604 (3.42) ^{***}
Mean sectoral proportion of science graduates	-0.005 (1.39)	-0.005 (1.32)	-0.005 (1.24)	-0.005 (1.20)
Logged employment size	0.089 (3.56) ^{***}	0.088 (3.50) ^{***}	0.088 (3.44) ^{***}	0.090 (3.58) ^{***}
Logged productivity		0.004 (0.13)		
¹ Logged productivity 2 nd quartile			0.081 (0.94)	
¹ Logged productivity 3 rd quartile			0.117 (1.34)	
¹ Logged productivity 4 th quartile			0.013 (0.15)	
Exporter * prod. interaction 2 nd qtile.				0.059 (0.55)
Exporter * prod. interaction 3 rd qtile.				0.016 (0.16)
Exporter * prod. interaction 4 th qtile.				-0.094 (0.83)
Later survey	1.044 (17.70) ^{***}	1.040 (17.47) ^{***}	1.038 (17.35) ^{***}	1.046 (17.48) ^{***}
Observations	2856	2832	2832	2832
Firms	734	732	732	732
LR χ^2	351.1	346.0	348.6	
Prob > χ^2	0.000	0.000	0.000	0.000

Notes:

Absolute value of z statistics in parentheses; Standard errors clustered on ID

* significant at 10%; ** significant at 5%; *** significant at 1%

¹ Baseline is first productivity quartile

Table 7 Marginal effects: Impact of Innovation on Environmental Abatement

	Coefficient estimates	$\frac{\partial P(y = 0)}{\partial x}$	$\frac{\partial P(y = 1)}{\partial x}$	$\frac{\partial P(y = 2)}{\partial x}$	$\frac{\partial P(y = 3)}{\partial x}$	$\frac{\partial P(y = 3)}{\partial x}$
						Exporters only
Firm is an exporter	0.194** (0.07)	-0.076** (0.028)	0.005 (0.003)	0.036** (0.013)	0.035** (0.012)	
Logged employment size	0.092*** (0.025)	-0.036*** (0.01)	0.002* (0.001)	0.017*** (0.005)	0.017*** (0.005)	0.019*** (0.005)
¹ Logged productivity 2 nd quartile	0.111 (0.086)	-0.043 (0.033)	0.002 (0.001)	0.02 (0.015)	0.021 (0.017)	0.023 (0.019)
¹ Logged productivity 3 rd quartile	0.189* (0.087)	-0.073* (0.033)	0.002 (0.001)	0.034* (0.015)	0.037* (0.018)	0.041* (0.020)
¹ Logged productivity 4 th quartile	0.191* (0.091)	-0.074* (0.034)	0.002 (0.001)	0.034* (0.016)	0.038* (0.019)	0.041* (0.021)
cut1						
_cons	1.014*** (0.165)					
cut2						
_cons	1.609*** (0.168)					
cut3						
_cons	2.449*** (0.173)					

Notes:

- (i) Marginal effects derived from ordered probit model (See Table 5)
- (ii) Standard errors robust to heteroskedasticity and within establishment serial correlation in parentheses.
- (iii) significant at 10%; ** significant at 5%; *** significant at 1%.
- (iv) Time dummies are included in the model as is sectoral FDI and sectoral skills
- (v) Marginal effects give the marginal effect of the relevant covariate on the probability of the establishment undertaking environmental innovation at the specified

level. For example, $\frac{\partial P(y = 3)}{\partial EXPORTER} = 0.035$ implies that EXPORTERS are 3.5 percentage points more likely to undertake very important environmental innovation than otherwise equivalent non-exporters.

Table 8 Marginal effects: Impact of Innovation in Reducing Energy & Materials Costs

	Coefficient estimates	$\frac{\partial P(y = 0)}{\partial x}$	$\frac{\partial P(y = 1)}{\partial x}$	$\frac{\partial P(y = 2)}{\partial x}$	$\frac{\partial P(y = 3)}{\partial x}$	$\frac{\partial P(y = 3)}{\partial x}$
						Exporters only
Firm is an exporter	0.757*** (0.123)	-0.182*** (0.029)	0.008 (0.005)	0.090*** (0.015)	0.085*** (0.013)	
Logged employment size	0.150*** (0.043)	-0.036*** (0.01)	0 (0.001)	0.018*** (0.005)	0.018*** (0.005)	0.022*** (0.006)
¹ Logged productivity 2 nd quartile	0.149 (0.145)	-0.035 (0.034)	0 (0.001)	0.018 (0.017)	0.018 (0.018)	0.022 (0.022)
¹ Logged productivity 3 rd quartile	0.203 (0.146)	-0.048 (0.034)	-0.001 (0.002)	0.024 (0.017)	0.025 (0.019)	0.030 (0.022)
¹ Logged productivity 4 th quartile	0.017 (0.147)	-0.004 (0.035)	0 (0.001)	0.002 (0.017)	0.002 (0.018)	0.002 (0.021)
cut1						
_cons	2.160*** (0.274)					
cut2						
_cons	3.047*** (0.284)					
cut3						
_cons	4.431*** (0.296)					

Notes:

- (i) Marginal effects derived from ordered probit model (See Table 6)
- (ii) Standard errors robust to heteroskedasticity and within establishment serial correlation in parentheses.
- (iii) significant at 10%; ** significant at 5%; *** significant at 1%.
- (iv) Time dummies are included in the model as is sectoral FDI and sectoral skills
- (v) Marginal effects give the marginal effect of the relevant covariate on the probability of the establishment undertaking environmental innovation at the specified

level. For example, $\frac{\partial P(y = 3)}{\partial EXPORTER} = 0.085$ implies that EXPORTERS are 8.5 percentage points more likely to undertake very important environmental innovation than otherwise equivalent non-exporters.

Table 9 Regression with Endogeneous Exporting: Impact of Innovation on Environmental Abatement/ Costs

	Environmental abatement		Costs	
	(1)	(2)	(3)	(4)
Firm is an exporter ⁽ⁱ⁾	0.69 (0.93)	1.27 (1.79)*	1.69 (2.33)**	1.07 (1.85)*
Logged employment size	0.10 (1.78)*	0.07 (1.19)	0.06 (0.99)	0.08 (1.76)*
Logged productivity 2 nd quartile	0.10 (0.66)	0.07 (0.41)	-0.05 (-0.29)	-0.14 (-0.09)
Logged productivity 3 rd quartile	0.20 (1.21)	0.15 (0.84)	-0.07 (-0.47)	-0.02 (-0.12)
Logged productivity 4 th quartile	0.37 (2.12)**	0.38 (1.99)***	-0.07 (-0.44)	-0.08 (0.61)
Anderson LR statistic (IV relevance test)	21.527	20.691	21.527	20.691
χ^2	0.000	0.000	0.000	0.000
Hansen statistic (for overidentification)	0.187	0.205	2.184	0.916
χ^2	0.666	0.651	0.139	0.339

Notes:

- (i) Models 1 & 3: Instruments for exporting status are total ratio of internationally imported inputs for UK firms in Republic of Ireland (4-digit level) and the lag of this
Models 2 and 4: Instruments as for 1 & 3 but we use median rather than average amounts at 4-digit sectoral level
- (ii) Standard errors robust to heteroskedasticity and within establishment serial correlation in parentheses.
- (iii) significant at 10%; ** significant at 5%; *** significant at 1%.
- (iv) Time dummies are included in the model as is sectoral FDI and sectoral skills

Table 10 Survey Cross-Section Results: Impact of Innovation on Abatement / Costs

Environmental abatement

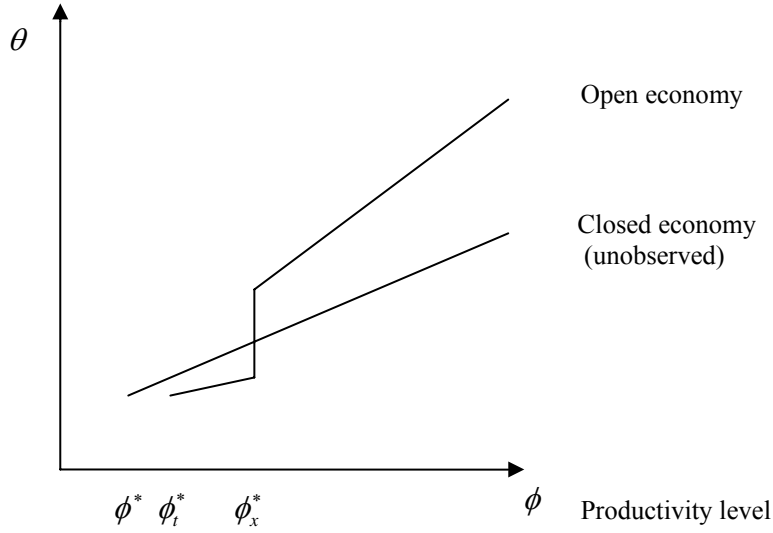
Costs

	CIS 3 (1998-2000)	CIS 4 (2000 – 2002)	CIS 3 (1998-2000)	CIS 4 (2000 – 2002)
Firm is an exporter	0.320 (3.08) ^{***}	0.107 (1.13)	0.618 (5.60) ^{***}	0.332 (3.57) ^{***}
Logged employment size	0.075 (2.15) ^{**}	0.109 (3.18) ^{***}	0.050 (1.38)	0.121 (3.72) ^{***}
Logged productivity 2 nd quartile	0.163 (1.41)	0.051 (0.42)	-0.031 (0.26)	0.190 (1.50)
Logged productivity 3 rd quartile	0.218 (1.82) [*]	0.159 (1.32)	0.092 (0.78)	0.153 (1.26)
Logged productivity 4 th quartile	0.081 (0.63)	0.264 (2.16) ^{**}	-0.186 (1.41)	0.161 (1.34)
Observations	1,442	1,390	1,442	1,390
Firms	721	695	721	695
Wald χ^2	41.25	24.24	76.36	44.23
Prob > χ^2	0.000	0.001	0.000	0.000
Pseudo r^2	0.0285	0.0128	0.0501	0.0229

Notes:

- (i) Standard errors robust to heteroskedasticity and within establishment serial correlation in parentheses.
- (ii) significant at 10%; ** significant at 5%; *** significant at 1%.
- (iii) Sectoral FDI and sectoral skills included in model

Figure 1 Firm's abatement technology effort and productivity level



Notes:

ϕ_x^* denotes the threshold productivity level for exports. Only firms with a productivity level higher ϕ_x^* export. ϕ^* denotes the threshold productivity level in the closed economy. Firms with a lower productivity level exit immediately.

ϕ_t^* denotes the threshold productivity level in the open economy. Firms with a lower productivity level exit immediately.

Figure 2
Predicted Prob. that Innovation has no Environmental Impact: By Productivity

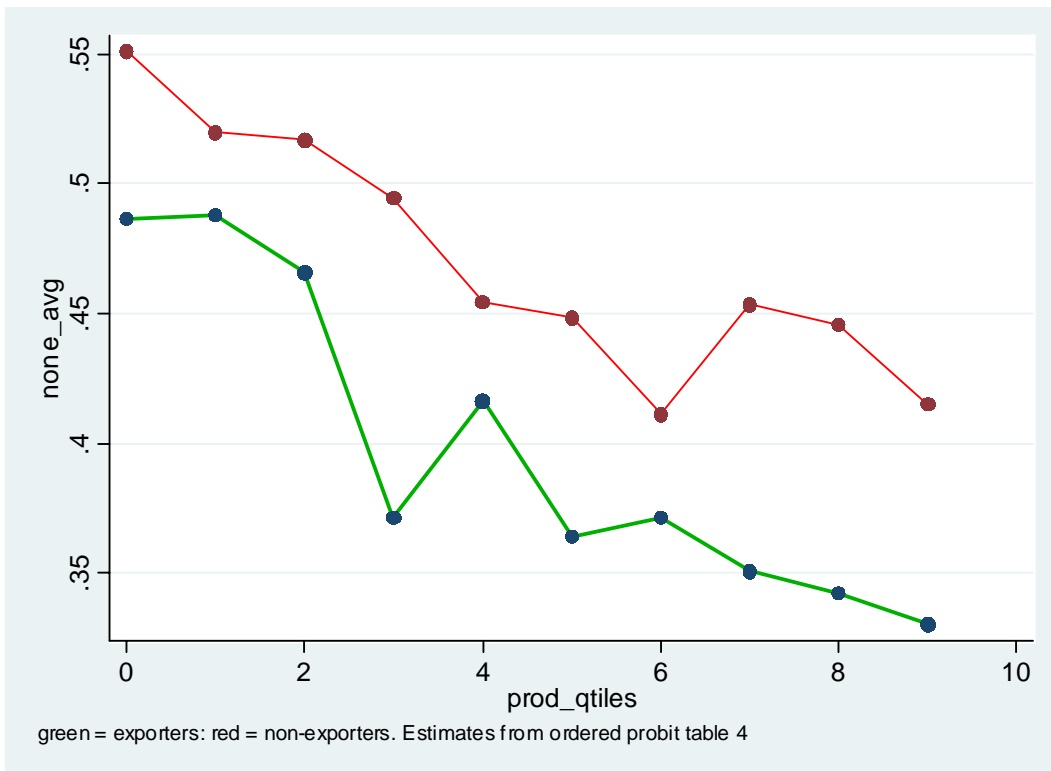


Figure 3

Predicted Prob. that Innovation has High Environmental Impact: By Productivity

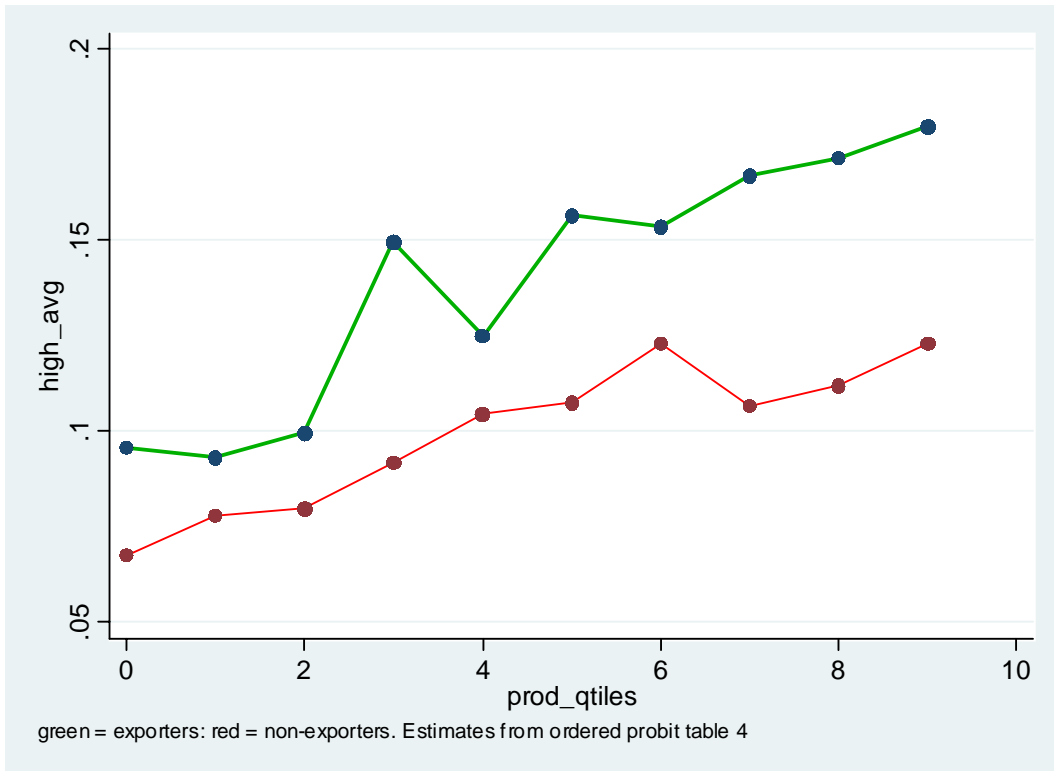


Figure 4

Predicted Prob. that Innovation has no impact on Costs: By Productivity

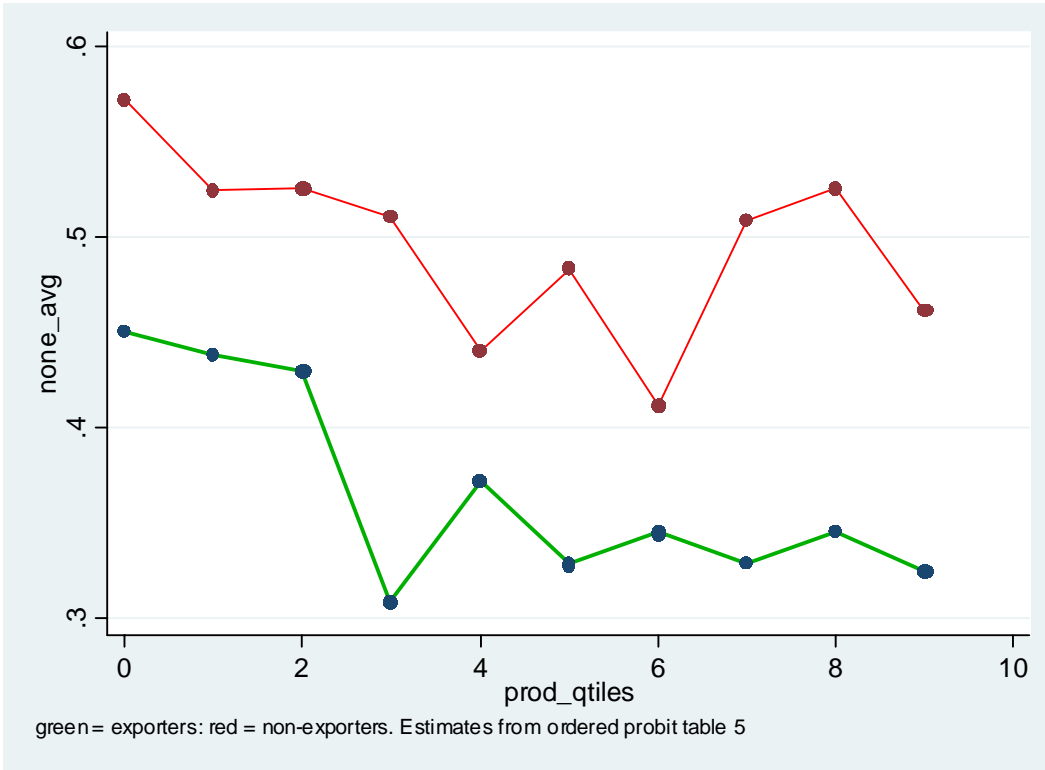
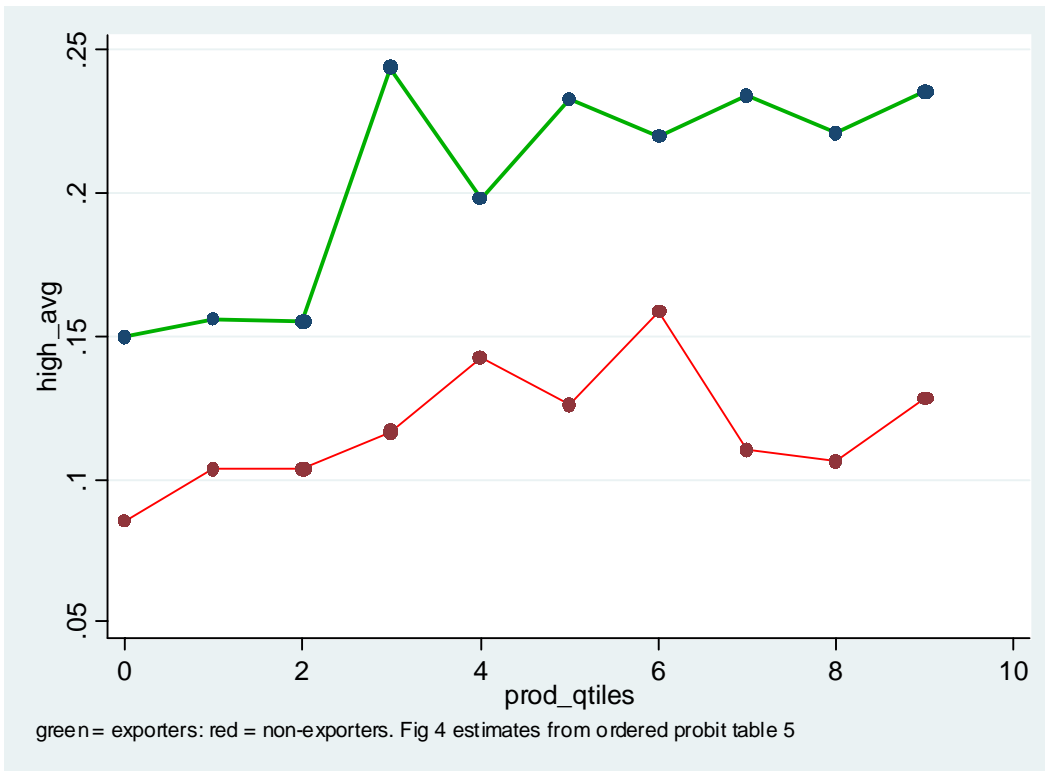


Figure 5
Predicted P. that innovation has high impact on Costs: By Productivity



Appendix 1: Proof, that a higher productivity level of a firm yields higher investment in pollution abatement technology, using the general framework

One can consider the two first-order profit maximization conditions as a set of simultaneous equations which defines a set of implicit functions.²¹ p and θ are functions of the exogenous variables and the parameters at and around any point that satisfies the first-order conditions.²²

$$F = \pi = \beta I \left[\frac{P}{P_S} \right]^{1-\sigma} - \left[\frac{1}{\phi} + z \tau \alpha(\theta) \right] \frac{\beta I}{P_S} \left[\frac{P}{P_S} \right]^{-\sigma} - f - c \theta$$

$$F_\theta = -z \tau \alpha'(\theta) \frac{\beta I}{P_S} \left(\frac{P}{P_S} \right)^{-\sigma} - c = 0$$

$$F_p = \beta I P_S^{\sigma-1} \left((1-\sigma) p^{-\sigma} + \sigma p^{-\sigma-1} \left(\frac{1}{\phi} + z \tau \alpha(\theta) \right) \right) = 0$$

We use the implicit function theorem to find the comparative-static derivative, $\frac{\partial \theta^*}{\partial \phi}$:

$$\frac{\partial \theta^*}{\partial \phi} = \frac{|J^{\phi/\theta}|}{|J|}$$

where $|J| = \begin{vmatrix} F_{\theta\theta} & F_{\theta p} \\ F_{p\theta} & F_{pp} \end{vmatrix}$ and $|J^{\phi/\theta}| = \begin{vmatrix} -F_{\theta\phi} & F_{\theta p} \\ -F_{p\phi} & F_{pp} \end{vmatrix}$.

The first order derivatives of the set of equations equal the second-order derivatives of the firm's profit function:

$$F_{\theta\theta} = \frac{\partial F_\theta}{\partial \theta} = -z \tau \alpha''(\theta) \frac{\beta I}{P_S} \left(\frac{P}{P_S} \right)^{-\sigma}$$

$$F_{p\theta} = F_{\theta p} = \frac{\partial F_\theta}{\partial p} = \sigma p^{-\sigma-1} z \tau \alpha'(\theta) \beta I P_S^{\sigma-1}$$

$$\begin{aligned} F_{pp} &= \frac{\partial F_p}{\partial p} = \beta I P_S^{\sigma-1} \left(-\sigma(1-\sigma) p^{-\sigma-1} + \sigma(-\sigma-1) \left(\frac{1}{\phi} + z \tau \alpha(\theta) \right) p^{-\sigma-2} \right) \\ &= -\sigma \beta I P_S^{\sigma-1} p^{-\sigma-1} \left((1-\sigma) + (\sigma+1) \left(\frac{1}{\phi} + z \tau \alpha(\theta) \right) p^{-1} \right) \end{aligned}$$

From first order conditions follows: $p = \frac{\sigma}{\sigma-1} \left(\frac{1}{\phi} + z \tau \alpha(\theta) \right)$

²¹ We can use the implicit function theorem if the Jacobinian $|J|$ is non-zero at the point which satisfies the simultaneous equations $F_\theta = F_p = 0$.

²² Chiang, pp 199

Using this condition we get:

$$F_{pp} = -(\sigma - 1)\beta IP_S^{\sigma-1} p^{-\sigma-1} < 0$$

This leads to:

$$\begin{aligned} |J| &= \begin{vmatrix} F_{\theta\theta} & F_{\theta p} \\ F_{p\theta} & F_{pp} \end{vmatrix} = z\tau a''(\theta) \frac{\beta I}{P_S} \left(\frac{P}{P_S}\right)^{-\sigma} (\sigma - 1)\beta IP_S^{\sigma-1} p^{-\sigma-1} - (\sigma\beta IP_S^{\sigma-1} p^{-\sigma-1} z\tau a'(\theta))^2 \\ &= z\tau(\beta IP_S^{\sigma-1})^2 p^{-2\sigma-2} (pa''(\theta)(\sigma - 1) - z\tau(\sigma a'(\theta))^2) \\ &= z\tau(\beta IP_S^{\sigma-1})^2 p^{-2\sigma-2} \sigma(a''(\theta)\left(\frac{1}{\phi} + z\tau a(\theta)\right) - \sigma z\tau(a'(\theta))^2) \\ &= z\tau(\beta IP_S^{\sigma-1})^2 p^{-2\sigma-2} \sigma\left(\frac{a''(\theta)}{\phi} + z\tau(a(\theta)a''(\theta) - \sigma a'(\theta)^2)\right) \end{aligned}$$

Certain regularities for the pollution abatement technology have to hold. Jacobian determinant $|J|$ to be positive at the point p^* and θ^* , I impose the restriction:²³

$$\frac{a''(\theta)}{\phi} + z\tau(a(\theta)a''(\theta) - \sigma a'(\theta)^2) > 0.$$

The specified technology function $a(\theta) = \frac{1}{\theta}$ and any $\sigma \leq 2$ fulfills this condition (the parenthesis $(a(\theta)a''(\theta) - \sigma a'(\theta)^2)$ is non-negative then, and $\frac{a''(\theta)}{\phi}$ always remains positive).

To derive $|J^{\phi/\theta}|$:

$$\begin{aligned} -\frac{\partial F_\theta}{\partial \phi} &= 0 \\ -\frac{\partial F_p}{\partial \phi} &= \beta IP_S^{\sigma-1} \sigma \phi^{-2} p^{-\sigma-1} \end{aligned}$$

²³ For the implicit function theorem to be applicable a non-zero Jacobian determinant would be sufficient. For the point p^* and θ^* to be a maximum, the Hessian determinant (which equals the Jacobian determinant at this point) has to be positive. This is satisfied when the stated restriction holds.

$$|J^{\phi/\theta}| = \begin{vmatrix} 0 & \frac{\partial F_\theta}{\partial p} \\ \beta I P_s^{\sigma-1} \sigma \phi^{-2} p^{-\sigma-1} & \frac{\partial F_p}{\partial p} \end{vmatrix} = -p^{-\sigma-1} z \tau a'(\theta) \beta I P_s^{\sigma-1} \beta I P_s^{\sigma-1} \sigma \phi^{-2} p^{-\sigma-1}$$

Consequently,

$$\begin{aligned} \frac{\partial \theta^*}{\partial \phi} &= \frac{|J^{\phi/\theta}|}{|J|} = \frac{-p^{-\sigma-1} z \tau a'(\theta) \beta I P_s^{\sigma-1} \beta I P_s^{\sigma-1} \sigma \phi^{-2} p^{-\sigma-1}}{z \tau a''(\theta) \frac{\beta I}{P_s} \left(\frac{p}{P_s}\right)^{-\sigma} (\sigma-1) \beta I P_s^{\sigma-1} p^{-\sigma-1} - (\sigma \beta I P_s^{\sigma-1} p^{-\sigma-1} z \tau a'(\theta))^2} \\ &= \frac{-a'(\theta) \phi^{-2}}{\frac{a''(\theta)}{\phi} + z \tau (a(\theta) a''(\theta) - \sigma a'(\theta)^2)} > 0 \end{aligned}$$

The optimal level of pollution abatement increases with higher firm productivity.

Appendix 2: Derivation of the optimal levels of p_d , p_x , and θ in the open economy

$$\pi_{D+X} = \beta I \left[\frac{p_d}{P_S} \right]^{1-\sigma} - \left[\frac{1}{\phi} + \frac{z\tau}{\theta} \right] \frac{\beta I}{P_S} \left[\frac{p_d}{P_S} \right]^{-\sigma} + \beta I \left[\frac{p_x}{P_S} \right]^{1-\sigma} - \left[\frac{1}{\phi} + \frac{z\tau}{\theta} \right] t \frac{\beta I}{P_S} \left[\frac{p_x}{P_S} \right]^{-\sigma} - f - c\theta - f_x$$

Maximize over p_d, p_x, θ :

$$(I) \pi_{p_{de}} = (1-\sigma)\beta I P_S^{\sigma-1} p_{de}^{-\sigma} + \sigma \left(\frac{1}{\phi} + \frac{z\tau}{\theta} \right) \beta I P_S^{\sigma-1} p_{de}^{-\sigma-1} = 0$$

$$(II) \pi_{p_x} = (1-\sigma)\beta I P_S^{\sigma-1} p_x^{-\sigma} + \sigma \left(\frac{1}{\phi} + \frac{z\tau}{\theta} \right) t \beta I P_S^{\sigma-1} p_x^{-\sigma-1} = 0$$

$$(III) \pi_{\theta} = \frac{z\tau}{\theta^2} \beta I P_S^{\sigma-1} p_{de}^{-\sigma} + \frac{z\tau}{\theta^2} t \beta I P_S^{\sigma-1} p_x^{-\sigma} - c = 0$$

$$p_{de} = \frac{\sigma}{\sigma-1} \left(\frac{1}{\phi} + \frac{z\tau}{\theta} \right)$$

$$p_x = \frac{\sigma}{\sigma-1} \left(\frac{1}{\phi} + \frac{z\tau}{\theta} \right) t = t p_{de}$$

Set $\sigma = 2$

Plug p_{de} into (III) and solve for θ :

$$\theta = \frac{\phi(\sqrt{cz\pi\beta I P_S(1+t)} - 2czt\tau)}{2ct} \quad (\text{positive solution})$$

Therefore,

$$p_{de} = \frac{2t\sqrt{cz\pi\beta I P_S(1+t)}}{\phi\sqrt{cz\pi\beta I P_S(1+t)} - 2czt\tau}$$

and

$$p_x = t p_{de}.$$

Appendix 3 Breakdown of other key covariates

		mean	sd	median	no.
productivity	1998-2000	122.8	241.7	75.8	1506
	2002-2004	147.7	243.8	89.7	1470
skills	1998-2000	6.8	13.5	2	1286
	2002-2004	6.27	12.8	1	1536
fdi	1998-2000	.4313	.2020	.4310	1474
	2002-2004	.4313	.2020	.4310	1474

Notes:

FDI is invariant over the period because it was taken from FAME, a balanced panel whose cross-section information is not updated each year. Hence we were unable to calculate changes in FDI

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