The Environmental Effects of Trade and Environmental Policy Within and Across Sectors

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This dissertation is dedicated to my beloved wife, Victoria.

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Abstract

In the first chapter of this dissertation I analyze how establishment-level choices and dynamics affect aggregate emissions outcomes. To do this I first decompose aggregate emissions into three channels: scale or country size, composition or sector market share, and aggregate technique or emissions intensity. I then extend the decomposition to show how the aggregate technique channel is driven by four establishment-level channels: entry, exit, reallocation of resources between survivors, and within-establishment adjustment of production techniques and emissions intensity. Using establishment-level emissions data and a unique empirical exercise I first show, empirically, how the relative importance of the composition and aggregate technique channels have evolved over time and that changes in aggregate emissions intensity have been the most important channel driving observed declines in aggregate emissions. I follow that up by decomposing the aggregate emissions intensity channel into the four component channels.

In the second chapter I combine within and across sector channels through which trade affects our environment by embedding heterogeneous firms and fixed costs into a two-sector representative-firm framework along with endogenous response to environmental policy. In contrast to existing literature that tends to examine these channels separately, the combined framework I develop shows how cross-sector and within-sector responses to trade and environmental policy interact to affect our environment.

Finally, in the third chapter I address the question, how does environmental policy affect aggregate emissions intensity when operating within and across firms? To do this, I develop a model with heterogeneous polluting firms to analyze how environmental regulation affects polluting industries and the environment. Firms within a particular industry differ in their productivity which influences their size and emissions intensity. The model allows me to decompose the effect of environmental regulation into two distinct channels: within firm changes in emissions intensity and techniques, and increased exit from the regulated industry. I then evaluate how changes in a unique measure of environmental policy affect environmental outcomes through these two channels in the presence of fixed costs using emissions data from U.S. manufacturing sectors from 1990 - 2007.

Table of Contents

1 Emissions Demand Within and Across Sectors: Identifying the Effective Channels **1**

1.1 Introduction . . . 2
1.2 Theory . . . 5
1.2.1 Within and Across Sector . . . 5
1.2.2 Within and Across Establishment . . . 5
1.3 Empirical Strategy . . . 8
1.3.1 Within and Across Sector . . . 9
1.3.2 Within and Across Establishment . . . 12
1.4 Robustness . . . 16
1.5 Conclusion . . . 18

2 The Environmental Effects of Trade Within and Across Sectors **20**

2.1 Introduction . . . 21
2.2 Setup . . . 24
2.2.1 Demand . . . 24
2.2.2 Production . . . 25
2.2.3 Integrated and free-trade equilibria . . . 30
2.2.4 Emissions Demand . . . 31
2.3 Environmental Policy in the Combined Framework . . . 33
2.3.1 Environmental dynamics . . . 35
2.4 The Environmental Role of Comparative Advantage . . . 35
2.5 Costly Trade . . . 38
2.5.1 Free Entry . . . 39
2.5.2 Goods and Factor Markets . . . 39
2.5.3 Costly Trade Equilibrium . . . 40
2.6 The Environmental Role of Firm Heterogeneity . . . 40
2.7 The Combined Effect . . . 42

2.8 Conclusion . . . 46

3 Environmental Policy in the Presence of Heterogeneous Firms 47

3.1 Introduction . . . 48
3.2 Theory . . . 51
3.2.1 Model . . . 51
3.2.2 Free Entry . . . 53
3.2.3 Aggregate Emissions Intensity . . . 54
3.2.4 Hypotheses . . . 56
3.3 Data . . . 60
3.3.1 Environmental stringency measure . . . 62
3.3.2 Fixed cost measure . . . 65
3.4 Identification and Results . . . 66
3.4.1 Empirical Specifications . . . 66
3.4.2 Identification . . . 66
3.4.3 Interpreting the Results . . . 68
3.4.4 Results . . . 68
3.5 Robustness . . . 72
3.5.1 Fixed Costs . . . 72
3.5.2 Environmental Stringency . . . 73
3.5.3 Capital Intensity . . . 74
3.6 Conclusion . . . 75

Bibliography 77

Appendix 84

A Chapter 1 Figures and Tables 85

B Chapter 2 Empirical Decomposition 97

C Chapter 2 Theory 100

D Chapter 3 Theory 112

E Chapter 3 Figures and Tables 117

Vita 129

List of Tables

A.1 Sample Comparison: RSEI (Pounds) 87
A.2 Sample Comparison: NETS (Sales and Employment) 88
A.3 Market Share and Entry Rates by Entrants and Exiters (RSEI) 90
A.4 Change in Aggregate Emissions Intensity by Channel 92
A.5 Change in Aggregate Emissions Intensity By Surviving Establishments . . . 93
A.6 Market Share and Entry Rates by Entrants and Exiters (NETS) 94
A.7 Sales Share and Entry Rates by Entrants and Exiters (NETS) 95

B.1 NEI Industry Groups 99

E.1 Summary Statistics: Dependent Variables 118
E.2 Evaluation of Environmental Regulation Measure 120
E.3 Evaluation of Fixed Cost Measure 121
E.4 Hypotheses 1 and 2: Regulation, Fixed Costs and Aggregate Emissions Intensity 122
E.5 Hypotheses 3 and 4: Regulation, Fixed Costs and the Mass of Firms 123
E.6 Hypotheses 5 and 6: Regulation, Fixed Costs and Average Emissions Intensity 124
E.7 Summary Statistics for Fixed Cost and Environmental Regulation 125
E.8 Three Measures of Fixed Costs on: Number of Firms, HHI, TFP 126
E.9 Alternative Measure of Environmental Stringency: PACE 127
E.10 Augmented Specification Including Capital Intensity 128

List of Figures

A.1 US Manufacturing Real Output, Imports, Exports, and Emissions 85
A.2 Variation in Emissions Within and Across SIC2-Sectors (RSEI) 86
A.3 Variation in Emissions Within and Across SIC4 Sectors (RSEI, Manufacturing) 86
A.4 Sample Comparison: RSEI (Pounds) 87
A.5 Sample Comparison: NETS (Sales and Employment) 88
A.6 Annual Aggregate Emissions Intensity 89
A.7 Exit Rate by Establishment Age: RSEI 91
A.8 Exit Rate by Establishment Age: NETS 95
A.9 Change in Aggregate Emissions Intensity - Comparison of Weights 96

B.1 Variation in Emissions Within and Across Sector Groups (NEI, SO2) 99

E.1 Within and Across Sector Variation in Emissions: NEI, SO2 (All Sectors, Sector Groups) 117
E.2 Distribution of Emission Intensity 119
E.3 Evolution of Average Non-Attainment Share Over Sample Period 119

Chapter 1

Emissions Demand Within and Across Sectors: Identifying the Effective Channels

1.1 Introduction

Pollution in the US has been declining steadily over the past several decades, while at the same time, the real value of output has been increasing.[1] This aggregate reduction in emissions has been due to a shift in the composition of production towards cleaner sectors, and reductions in aggregate emissions intensity across sectors. The shifts in composition of production arise due to changes in relative prices–for example, due to to reductions in trade barriers stimulating increased imports and exports[2] or changes in regulatory policy–and the resulting cross-sector shift of resources according to sectors' comparative advantages. The reduction in aggregate emissions intensity, however, could be the result of several general equilibrium channels. In particular, the reduction in aggregate emissions intensity could be due to adjustment of production techniques and investment in abatement on the part of all operating establishments; It could also be the result of resources being reallocated, within sectors, to relatively more productive and less emissions intense establishments; And, finally, it could be due to the exit of emissions-intense incumbents and the entry of relatively clean establishments. This paper addresses the question: how much of the observed reduction in aggregate emissions comes from reductions in aggregate emissions intensity, and how important are each of the four establishment-level channels–exit, entry, cross-establishment reallocation, and within-establishment adjustment of production techniques–in driving changes in aggregate emissions?

I begin my analysis by decomposing aggregate emissions into three channels: "scale" (changes in total output or country size over time), "composition" (changes in sectors' market share over time), and aggregate "technique" (change in aggregate emissions intensity due to changes in production techniques employed over time). A similar decomposition was first suggested by Grossman and Krueger (1994) and has been regularly used in related literature seeking to understand the effects of trade and regulatory policy on environmental outcomes, including Antweiler et al. (2001); Cole and Elliott (2003); Levinson (2009). I extend this decomposition, by modifying a method developed by Melitz and Polanec (2015), to show that the aggregate technique effect is in fact driven by four establishment-level channels: reallocation of resources among entering, exiting, and surviving establishments, and within-establishment adjustment to production techniques and emissions intensity. This allows me to directly link establishment-level changes to aggregate emissions outcomes.

[1] This is the case both in the US in general, as documented by the EPA (see US Environmental Protection Agency Air Quality Report, 2012), as well as in US manufacturing in particular, as can be seen in Figure (A.1).

[2] Along with output, trade volume has also increased dramatically in the last several decades, as can be seen in Figure (A.1)

I then employ establishment-level emissions data from the EPA's Risk Screening and Environmental Indicators (RSEI) database, using a technique suggested by Mundlak et al. (2012), to show the relative importance of the cross-sector composition and within-sector aggregate technique channels and how these channels evolve over time. These results show that both across-sector and within-sector channels are important determinants of observed changes in aggregate emissions, but that changes in the within-sector aggregate emissions intensity channel is most important. This result parallels a related analysis in Levinson (2009).[3] I then build on this insight, and the theoretical decomposition, to show the relative empirical importance of each of the four establishment-level channels driving aggregate emissions outcomes through the aggregate technique effect. The results show that, while entry and exit are both important channels driving changes in aggregate emissions intensity, reductions among surviving establishments are by far the most substantial channel driving the observed decline in aggregate emissions intensity. Contributions by survivors account for roughly five-times the contribution of entrants, and nearly three-times that of exiting establishments. I further show that, among surviving establishments, reallocation towards less emissions-intense establishments and within-establishment adjustment to production techniques are of similar importance.

Similar decompositions have been applied at various times in the broader literature, for example Foster et al. (2001) and Griliches and Regev (1995) evaluate the establishment-level channels driving changes in employment, productivity, output, and other industrial characteristics. In addition, numerous studies have used establishment level data to analyze environmental outcomes and policy changes, including Holladay (2016); Cui et al. (2015); Becker et al. (2013b); Shapiro and Walker (2015); Heutel (2011) and Shadbegian and Gray (2005). However, this is the first application of this type of decomposition, of which I am aware, applied to aggregate emissions outcomes to analyze the relative importance of establishment entry, exit, reallocation among survivors, and within-establishment adjustments to production techniques. Understanding the relative importance of individual firm decisions and sector-level outcomes for aggregate emissions outcomes is an important step that existing establishment-level empirical analysis has generally skipped over.

The empirical insights yielded by the analysis in this paper have the potential to make significant contributions to existing theoretical work as well. For example, regarding the effects of trade and environmental policy on the environment, two very different theoretical

[3]Levinson uses a different empirical approach to examine how scale, composition and technique effects changed from 1987 - 2001 and shows that declines in aggregate emissions intensity accounted for roughly 76 percent of the total decline in emissions.

approaches have been developed. On the one hand, Copeland and Taylor (2003) develop a two-sector international model built on comparative advantage, in which changes in trade or environmental policy influence relative prices and drive resources across sectors according to a country's comparative advantage. Changes in environmental policy also induce a within-establishment effect causing establishments to invest in abatement and reduce their emissions intensity. On the other hand, Kreickemeier and Richter (2013) develop a model which ignores both the cross-sector reallocation and within-establishment adjustment channels. Their approach focuses solely on how changes to trade costs or the fixed costs faced by establishments can cause systematic entry and exit by heterogeneous establishments that can thereby lead to higher aggregate productivity, lower aggregate emissions intensity and lower aggregate emissions. My empirical results contribute new evidence directly relating to these two theoretical approaches by showing the relative importance of the across-sector and within-sector channels, and the relative importance of entry, exit, and within-establishment adjustment to production techniques, in driving observed changes in aggregate emissions.

These results are also generally important for those concerned with the design of efficient environmental policy as well as those interested in better understanding and evaluating the means by which policy changes work to affect environmental outcomes. Traditional modeling approaches generally assume that identical, perfectly competitive plants respond in the same way to industry-wide shocks to policy or the economic environment. The results presented here expose a much more varied picture, consistent with a market comprised of heterogeneous firms that respond to different types of policy shocks in systematically different ways.[4] Under the policy regimes in place from 1990 - 2006, roughly 65 percent of the observed changes in aggregate emissions intensity were due to changes among survivors–split between within establishment adjustments to production techniques and resource reallocation to other firms–and roughly 35 percent were due to the contribution of entering and exiting establishments. Understanding how these dynamic responses change in response to policy changes or other economic shocks has important implications for employment, output, productivity, and general welfare.

The remainder of the paper is organized as follows: In the following section I lay out the theoretical decomposition that forms the link between the aggregate and establishment-level results. Section 3 discusses the data used, definitions, empirical techniques, and results for the two decompositions. Section 4 provides two robustness exercises, and section 5 concludes.

[4]E.g. Hopenhayn (1992) presents a dynamic model of entry and exit in which heterogeneous firms respond in systematically different ways to the presence and level of fixed costs. Melitz (2003) extends the heterogeneous model to monopolistic competition and includes trade costs.

1.2 Theory

1.2.1 Within and Across Sector

To understand how much of the observed declines in aggregate emissions are due to reductions in aggregate emissions intensity, I follow Levinson (2009) and decompose aggregate emissions into a national output or scale channel, a cross-sector comparative-advantage channel, and a within-sector aggregate emissions intensity or technique channel. Letting m denote an industry or sector, total emissions, Z, in a given year, t, can be decomposed into these three separate channels:

$$Z_t = \sum_m Z_{mt} = \sum_m Q_{mt} EI_{mt} = \underbrace{Q_t}_{\text{Scale}} \times \sum_m \underbrace{\Theta_{mt}}_{\text{Composition}} \cdot \underbrace{EI_{mt}}_{\text{Aggregate Technique}} \tag{1.1}$$

where $\Theta_{mt} = \frac{q_{mt}}{Q_t}$ represents the market share held by the sector and $EI_{mt} = \frac{Z_{mt}}{Q_{mt}}$ represents the aggregate emissions intensity of the sector. Thus, changes in aggregate emissions are driven by changes in country size or total output, changes in the relative market shares of cleaner and dirtier sectors, and changes in aggregate emissions intensity. Note that if a country were comprised of only a single sector, Θ_{mt} would equal one in each year, and there would be no composition effect. In this case, changes in aggregate emissions within any given year would be driven solely by the Aggregate Technique effect.

1.2.2 Within and Across Establishment

To understand how establishment-level adjustment can affect aggregate emissions, working through the Aggregate Technique effect, I extend the decomposition in (1.1). I add an additional subscript, n, to denote individual establishments. To aid the notation, in addition to using subscripts, I represent establishment-level variables with lower-case letters and aggregated variables with upper-case letters.

Using the fact that emissions in a given sector are merely the sum of the emissions of each establishment in that sector, $Z_{mt} = \sum_{n \in m} z_{nmt}$, I can further decompose the aggregate emissions intensity component from (1.1) in the following manner:

$$EI_{mt} = \underbrace{\sum_n \underbrace{\theta_{nmt}}_{\text{Reallocation}} \cdot \underbrace{ei_{nmt}}_{\text{Technique}}}_{\text{Aggregate Technique}} \tag{1.2}$$

where $\theta_{nmt} = \frac{q_{nmt}}{Q_{mt}}$ represents a establishment's share of output in their current sector, and $ei_{nmt} = \frac{z_{nmt}}{q_{nmt}}$ represents a establishment's emissions intensity. The "Reallocation" effect

captures changes in aggregate emissions intensity that occurs as establishments enter and exit and resources are systematically reallocated between establishments–an across-establishment effect–while the "Technique" effect captures adjustment in establishment's production techniques–a within-establishment effect. Written in this way, aggregate emissions intensity is essentially a share-weighted average of establishment's emissions intensity. Since this establishment-level analysis is inherently a sub-sector analysis, I drop the sector subscripts through the remainder of the discussion.

To understand the relative importance of reallocation, in its various forms, and within-establishment production technique adjustment in driving aggregate emissions, I examine the change in aggregate emissions intensity over time (from $t = 1$ to 2): $\frac{\Delta EI}{\overline{EI}} = \frac{EI_2 - EI_1}{\overline{EI}}$, where the weight $\overline{EI}$ is included to express the change in scale-independent terms.[5] I then modify an approach suggested by Melitz and Polanec (2015),[6] to decompose changes in aggregate emissions intensity into three channels–the shares due to survivors, entrants, and exiters–and then further decompose those channels into changes due to across-establishment reallocation and within-establishment adjustment.

Let $\Theta_{Gt} = \sum_{n \in G} \theta_{nt}$ represent the aggregate market share of a group, G, of establishments, where the G represents survivors (S), exiters (X), or entrants (E). Then define $EI_{Gt} = \sum_{n \in G} \left(\frac{\theta_{nt}}{\Theta_{Gt}} \right) ei_{nt}$ as the group's aggregate average emissions intensity.[7] Aggregate emissions intensity in each period can now be expressed as a function of the aggregate output share and aggregate emissions intensity of the three groups of establishments (survivors, entrants, and exiters):

$$\begin{aligned} EI_1 &= \Theta_{S1} EI_{S1} + \Theta_{X1} EI_{X1} = EI_{S1} + \Theta_{X1}(EI_{X1} - EI_{S1}) \\ EI_2 &= \Theta_{S2} EI_{S2} + \Theta_{E2} EI_{E2} = EI_{S2} + \Theta_{E2}(EI_{E2} - EI_{S2}) \end{aligned} \tag{1.3}$$

The final step of the decomposition builds on Olley and Pakes (1996) using the following alternative decomposition of aggregate emissions intensity:

$$\begin{aligned} EI_t &= \overline{ei}_t + \sum_n (\theta_{nt} - \overline{\theta}_t)(ei_{nt} - \overline{ei}_t) \\ &= \overline{ei}_t + \text{cov}(\theta_{nt},\, ei_{nt}) \end{aligned} \tag{1.4}$$

[5] $\overline{EI} = \frac{EI_1 + EI_2}{2}$

[6] Melitz and Polanec (2015) use a similar approach to decompose the channels underlying changes in aggregate productivity over time.

[7] Note that $\frac{\theta_{nt}}{\Theta_{Gt}}$, $\forall n \in G$, is always less than one.

where $\overline{ei}_t$ is the unweighted average establishment emissions intensity and $\overline{\theta}_t$ is average market share.[8] In this way, changes in aggregate emissions intensity can be expressed as changes in unweighted average emissions intensity, $\Delta\overline{ei}$–this can be thought of as a within-establishment effect that is common to all establishments–and the change in the covariance (between market share and emissions intensity), Δcov–which can be thought of as a cross-establishment reallocation effect. As discussed by Melitz and Polanec (2015), expressing the results in scale-independent terms when decomposing data measured in levels, as I will do, will also require a scale-independent covariance measure that will also be invariant to proportional changes in emissions intensity. I follow their lead in defining such a measure as $\widetilde{\text{cov}} = \text{cov}(\theta,\, ei/EI) = \text{cov}(\theta,\, ei)/EI$. Thus, $\widetilde{\text{cov}}$ represents the share of aggregate emissions intensity, EI, driven by the correlation between market share and emissions intensity, a cross-establishment share, and the remaining share, $\bar{ei}/EI$, captures the share due to average emissions intensity, independent of its correlation with market shares.

Combining the equations in (1.3) with the decomposition in (1.4), the change in aggregate emissions intensity is thus given by:

$$\begin{aligned}\frac{\Delta EI}{\overline{EI}} &= \frac{EI_{S2} - EI_{S1}}{\overline{EI}} + \frac{\Theta_{E2}(EI_{E2} - EI_{S2})}{\overline{EI}} + \frac{\Theta_{X1}(EI_{S1} - EI_{X1})}{\overline{EI}} \\ &= \frac{\Delta\overline{ei}_S}{(1-\overline{\widetilde{\text{cov}}}_S)\overline{EI}} + \frac{\Delta\text{cov}_S}{(1-\overline{\widetilde{\text{cov}}}_S)}\frac{\overline{EI}_S}{\overline{EI}} + \frac{\Theta_{E2}(EI_{E2} - EI_{S2})}{\overline{EI}} + \frac{\Theta_{X1}(EI_{S1} - EI_{X1})}{\overline{EI}} \quad (1.5)\end{aligned}$$

where $\overline{EI}_S = (EI_{S2} + EI_{S1})/2$ and $\overline{\widetilde{\text{cov}}}_S = \left(\overline{\widetilde{\text{cov}}}_{S2} + \overline{\widetilde{\text{cov}}}_{S1}\right)/2$ represent time average over periods 1 and 2.

The first line decomposes the percent change in aggregate emissions intensity into the share due to survivors, entrants, and exiting establishments. The second line further decomposes the change due to survivors into the change in the distribution of emissions intensity (which can be thought of as a within-establishment adjustment in production techniques that is common to all surviving establishments) and the change due to market share reallocation between cleaner and dirtier establishments (an across-establishment reallocation of resources among survivors).[9] This decomposition has several advantages.

First, the decomposition in the second line cleanly separates changes in aggregate emissions intensity into the four possible channels identified by existing theory: reallocation to entrants, reallocation away from exiting establishments, reallocation among surviving establishments, and within-establishment adjustment to production techniques and emissions

[8] Melitz and Polanec (2015) note that the use of the covariance operator, which would typically be multiplied by $1/n_t$, is a slight abuse of notation, but, because θ_{nt} are shares, the equation basically already incorporate this division.

[9] The same Olley and Pakes decomposition could be extended to entering and exiting establishments as well.

intensity, while still maintaining its link to the aggregate decomposition in equation (1.1) that is commonly used in related literature. Second, as noted by Melitz and Polanec (2015), this approach leverages the cross-sectional nature of the Olley and Pakes approach, and thus the decomposition into survivors, exiting, and entering establishments need not use the same reference emissions intensity value for each group, but are only constrained so that the sum of the three changes sum to the actual total change. Other decompositions used in related literature, for example Foster et al. (2001), include a fixed reference group–either establishments from a single period, or an average from multiple periods–and thus tend to miss trends in productivity, which Melitz and Polanec (2015) argues introduces bias, tending to understate the relative contribution of survivors. Finally, as formulated, the three channels have an intuitive interpretation. For example, the change due to survivors is the change in aggregate emissions intensity that would have occurred if there were no entry and exit. Then, using surviving establishments as a benchmark, the change due to entry, $\Theta_{E2}(EI_{E2} - EI_{S2})$, is the change in aggregate emissions intensity that would occur from adding or subtracting the entrants. Thus, entering establishments will contribute to a decline in aggregate emissions intensity if they have lower aggregate emissions intensity than survivors in period two, $EI_{E2} < EI_{S2}$. Similarly, exiting establishments will contribute to a decline in aggregate emissions intensity if they have a higher aggregate emissions intensity than surviving establishments, $EI_{X1} > EI_{S1}$.

1.3 Empirical Strategy

To understand how important establishment-level adjustment–via cross-establishment reallocation and within-establishment adjustments to production techniques–have been, relative to cross-sector reallocation of resources, in explaining the observed declines in aggregate emissions, I employ two separate empirical techniques. The first empirical approach I use allows me to compare the relative importance of the "composition" (Across Sector) and "aggregate technique" (Within Sector) effects, from equation (1.1), over time. Little to no evidence of a composition effect would suggests that all variation in aggregate emissions are driven by idiosyncratic differences across establishments, and not by systematic differences between groups of establishments that are similar in some dimension or set of characteristics. The second empirical technique allows me to analyze the relative importance of entry, exit, reallocation (Across Establishment), and adjustments to production techniques that establishments undertake (Within Establishment) that drive the aggregate technique effect.

1.3.1 Within and Across Sector

To analyze the relative importance of the across-sector composition and the within-sector aggregate technique channels, I make use of a method suggested by Mundlak et al. (2012), using fixed effects to determine the relative importance of cross-sector and within-sector variation in emissions, and then examine how those channels evolve over time.

Specification

Regressing time and sector fixed effects (a_t and a_s, respectively) on a panel of individual establishment specific emissions data, E_{nst}, allows me to decompose the total sum of squares into two orthogonal components, variation within sector (w_{st}) and variation across sector (a_s), in each period:

$$Emissions_{nst} = w_{st} + a_s + a_t$$

Thus, the within-sector variation is the residual effect remaining after accounting for cross-sector variation in the emissions variable. The cross-sector and within-sector variation are then expressed as a share by dividing by the total sum of squares in each year, and plotted over time.

Data

To analyze the relative share of variation in emissions over time that is due to the across-sector channel and the within-sector channel, I require establishment-level emissions and their corresponding parent industry categorization. The data set I make use of comes from the EPA's Toxic Release Inventory (TRI), which compiles reported pollution emissions by chemical for thousands of toxic chemicals regulated under the Emergency Planning and Community Right-to-Know Act (EPCRA). The database is made publicly available by the US Environmental Protection Agency (EPA) and includes minimal establishment-specific information including geographic location, and the establishment's sector, given by either four-digit Standard Industrial Classification (SIC4) or six-digit North American Industrial Classification System (NAICS) code. All U.S. facilities that meet the following three thresholds are required report the quantity of all chemicals used over the course of the year and how any of those chemicals were disposed, including air and water releases as well of off site management and recycling: Any facility (1) with more than 10 full-time-equivalent employees,[10] that (2) produce, process, or otherwise use more than a threshold

[10] I.e. 20,000 hours of payroll.

level of a regulated chemical in a year[11] and is (3) classified either in manufacturing, aspects of mining, some utilities, a small number of other miscellaneous industry groups, or as a federal facility.

The establishment data are then aggregated into a single output measure (a toxicity-weighted measure is also produced) that can be used to compare establishment performance over time. These aggregate measures are released in the Risk Screening and Environmental Indicators (RSEI) database. The TRI pollutants have been widely used in economics literature, but they are an imperfect measure of emissions due in part to their reporting requirements. There is also evidence that establishments may under-report their emissions in specific industries (Koehler and Spengler (2007)) and across all industries de Marchi and Hamilton (2006)). The RSEI data has been used in several studies to proxy for environmental performance of establishments, and communities.[12] In addition, the RSEI data are released annually, from 1990 - 2014, and it is one of few federal databases that has maintained the SIC codes alongside the newer NAICS and thus facilitates straightforward aggregate analysis across time. In addition, although the required list of chemicals has been adjusted over time, the database includes flags for the specific chemicals whose reporting requirements have changed, thus facilitating time-series analysis on a constant set of chemicals.[13]

Definitions and Results

The primary concern for this type of within and across sector analysis is how to define sectors. On the one hand, in the model developed by Antweiler et al. (2001), incorporating a role for cross-country comparative advantage driving the composition effect, there are two sectors, one dirty and one clean, in which the establishments in each "sector" make use of sector-specific technology which in turn implies different factor intensity in each sector. From this perspective, the sectors would be defined as very aggregated and highly distinct groups (e.g. manufacturing and services). On the other hand, related work by Dean and Lovely (2010), using Chinese manufacturing data broken into (sub) "sectors" defined by SIC2, and Levinson (2009), using US manufacturing data broken into (sub) "sectors" defined by SIC4, both observe that the non-trivial cross-sector composition effects they find could actually be understated, since their level of aggregation, within manufacturing, could be missing

[11] A common threshold is 10,000lbs but more toxic PBT chemicals have lower thresholds ranging down to 0.1-grams for dioxin.

[12] See Holladay (2016) for an establishment level example from the trade and environment literature and Banzhaf and Walsh (2008) for analysis on the community level for examples.

[13] The analysis presented here makes use of all chemicals with the the 1988 chemical flag which flags chemicals whose reporting requirements have not changed from the initial year of the TRI reporting requirement in 1988.

additional "cross-sector" variation that is occurring at even finer levels of dis-aggregation. To address these two perspectives I present results using two alternative sector definitions.

First, I use the RSEI data, grouping establishments by their two-digit SIC category, thus still presenting a rather aggregated definition of sectors.[14] These results are presented in Figure (A.2). The change in data sources and definitions yields different results in a couple of important ways. First, the data are available each year from 1990-2006, and provide a fairly consistent trend over the time period. Second, the variation explained by across-sector variation begins clearly climbing from the mid-1990's–though the majority of observed variation is explained by within-sector channels. The data clearly shows that both within and across sector variation are important channels driving observed emissions outcomes, and the cross-sector composition component has been rising in importance almost every year fro 1990.

The second analysis follows Dean and Lovely (2010) and Levinson (2009) by focusing on US manufacturers in the RSEI database, with establishments grouped by their four-digit SIC.[15] These results are presented in Figure (A.3). Including more dis-aggregated sector identifiers introduces two additional insights into the factors driving aggregate emissions outcomes. First, a greater share of variation throughout the panel is explained by across-sector variation. While it may seem intuitive at first that decomposing variation into less aggregated sector groups would mechanically result in more variation being explained by those sector groupings, it is worth considering that if the sub-sector categories were randomly assigned, the inclusion of those sub-sector indicators would actually be unlikely to increase the explanatory power of the cross-sector component. The fact that the inclusion of sub-sector identifiers does increase the explanatory power of the cross-sector composition component suggests that there are additional systematic differences across these sub-sector groupings that are important factors determining emissions outcomes. Second, the rise in relative importance of the cross-sector composition channel can be observed starting with the first year of the panel and continuing in almost every subsequent year. These results show quite clearly that both across- and within-sector channels driving observed aggregate emissions outcomes are important and worth continued scrutiny.

While the results from each of the sector definitions yielded the insight that cross-sector composition changes are an important element driving observed emissions changes, they also consistently show that the majority of observed changes in aggregate emissions–between 60 and 90 percent, depending on the sector definition–are driven by the within-sector aggregate

[14]The analysis includes 56 two-digit sectors, ranging from 01 to 99, and 406,821 establishment-level observations over the period.

[15]Nearly 93 percent of the observations in the RSEI database are from manufacturing sectors (SIC2 20 - 39).

technique or aggregate emissions intensity effect, delineated in equation (1.1) and expanded in equation (1.2) . Therefore, to further understand the role of individual establishment choices in determining aggregate emissions outcomes, I turn now to evaluate the importance of changes within and across establishments, that drive observed changes in aggregate emissions intensity.

1.3.2 Within and Across Establishment

To analyze the relative importance of the channels driving changes in the within-sector aggregate technique effect, I use the decomposition in (1.5) in conjunction with establishment-level emissions and production data from a sample of US manufacturing establishments to evaluate the importance of the various channels that drive changes in aggregate emissions intensity: reallocation of resources among entering, exiting, and surviving establishments, and within-establishment adjustment to production techniques. This decomposition approach builds on Melitz and Polanec (2015), as described in the previous theory section.

Data

The emissions data come from the RSEI database, described above, and I focus on US manufacturing establishments.[16] Establishment-level emissions intensities and sales-share weights are calculated using matched sales data from the National Establishment Time Series database. The NETS is compiled from Dunn and Bradstreet data on creditworthiness by Walls and Associates. Dunn and Bradstreet collect establishment level information that is used to generate credit scores. These scores are required to receive government contracts and are regularly used to make decisions regarding payment terms, leasing equipment or office space and setting financing terms. The data are collected by surveying establishments, tracking payment histories with other establishments and through research in trade publications and news archives. Neumark et al. (2011) analyze the NETS data and compare them to data collected by the Current Population Survey (CPS) and the Current Employment Statistics (CES) Payroll Survey. They find that the NETS data on employment are of comparable quality to the CPS and CES.[17] They also use a media search to find reports of plant relocation. The NETS reflected around three-quarters of the moves that crossed a

[16] This analysis will, thus, be most consistent with an aggregate "group" analysis that treats "manufacturing" as a sector. It can easily be conducted on each of the sub-groups within manufacturing as well by defining sectors at the two, three, or four digit level, etc.

[17] County-by-Sector comparisons of the data yielded correlation of 0.99 with CES and 0.95 with CPS.

county or city line. That rate is similar to the rates found in Lexis-Nexis and Hoovers.com company location data sets.[18]

The NETS sample includes 251,879 establishments with parent establishment, industry, sales, employment and location information, and an indicator for establishment entry and exit, from 1990 - 2007. These observations are matched to annual establishment-level emissions data from the RSEI database. The matched RSEI-NETS sample includes 19,396 establishments (151,167 total observations). To evaluate the quality of the matched sub-sample and whether the observations in RSEI-NETS sample are representative of their respective parent databases, I compare the sample statistics and distributions of the key data in the parent data sets and the matched sub-sample. I report the sample statistics for emissions in the full RSEI and the RSEI-NETS matched panel in Table (A.1), and I compare the distribution of emissions from each sample, measured in natural logs, in Figure (A.4). The sub-sample matches roughly half of the observations in the full RSEI database. While the matched sample does not capture the same degree of variation in the parent sample, the median and mean are quite close and the distributions of log-emissions are quite similar. I also report the sample statistics for employment and sales in the full NETS and the RSEI-NETS matched panel in Table (A.2), and I compare the distribution of employment and sales, measured in natural logs, in Figure (A.5). The sub-sample matches a little over six percent of the observations in the NETS database, and the sample of matched establishments appears to be larger, on average, than establishments in the full NETS data set. This may be due to the reporting requirement of the TRI, under which establishments producing, processing, or using less than the threshold levels of the regulated chemicals are not required to report. To the extent that there are polluting establishments operating below the TRI threshold, they are more likely to be smaller establishments.

Aggregate Emissions Intensity Over Time

With this data in hand, I first evaluate the trend in baseline aggregate emissions intensity over time, where baseline aggregate emissions intensity is merely the ratio of the sum of establishment emissions, from the RSEI database, to the sum of establishment output in

[18] Haltiwanger et al. (2013) also discuss the quality of the NETS data and compare it to proprietary longitudinal data from the US Census LDB. They note that the NETS, with 14.7 million establishment in a typical year, appears to be comprised of some combination of employer and non-employer businesses but does not appear to contain the universe of employer and non-employer observations reported by the Census (an average of 7 million establishments per year with at least one employ, and an additional 15 million non-employer establishments). Further discussion of the merits of the NETS data can be found at youreconomy.org

each year.[19] This trend is plotted in Figure (A.6), which shows aggregate emissions intensity declining roughly 70 percent from 1990 to 2006.[20]

Empirical Approach

In order to evaluate the role of establishment entry and exit, cross-establishment reallocation, and within-establishment technique adjustments in driving the decline in aggregate emissions, working through the decline in aggregate emissions intensity, I make use of the modified decomposition given in equation (1.5). In addition to establishment emissions intensity data, this approach requires an establishment weighting measure, and a way of identifying establishment entry and exit.

For establishment-level weights I utilize output-shares, which has two important advantages. First, it allows me to maintain a straightforward link between the aggregate decomposition–incorporating scale and composition channels–in equation (1.1) and the additional establishment-level decomposition in (1.2). Second, using output-shares as weights, and calculating aggregate emissions intensity as in equation (1.2) exactly replicates the aggregate emissions intensity baseline trend, as can be seen in Figure (A.6). In a later section I explore and discuss several alternative weighting choices as a robustness exercise.

I define entry and exit as occurring when a establishment begins reporting and stops reporting (respectively) to the TRI, as identified by their existence in the data set. As discussed above, only establishments above certain employment and chemical-use thresholds are required to report to the TRI. Thus, polluting establishments may legally exit the data set, but still be in operation. To the degree that this type of administrative adjustment occurs overtime, this approach will overstate the importance of entry and exit, and understate the importance of adjustment and reallocation by surviving establishments. Table (A.3) reports the annual market share for entrants and exiters, and compares the entry and exit rates in the sample to those reported in the US Census Business Dynamics Statistics database.[21] Market size for entrants ranges from a low of 1.8 percent, in 2006, to a high of 10.3 percent in 2000, and for exiters from a low of 4 percent in 2003 to a high of 9.8 in 2000. In addition, although the rates of entry and exit are generally higher than those reported in the Census data, they are not always higher, and, on average, entry in the matched sample is only 0.7 percentage points higher than that reported by the Census, and exit is only 2.1 percentage points higher. Finally, I also document the rate of exit, by establishment age in Figure

[19] Real output is calculated as establishment sales, divided by the corresponding sector-specific price index, taken from the NBER-CES database described by Becker et al. (2013a).

[20] A similar decline in aggregate emissions intensity is documented, using an alternative method, by Levinson (2009).

[21] See http://www.census.gov/ces/dataproducts/bds/data_firm.html

(A.7).[22] The results show a distinct decline in the exit rates as establishments age and are quite similar to those documented by Clementi and Palazzo (2016), and Dunne et al. (1989) who use longitudinal data from the US Census.

Results

The results from the decomposition, set forth in equation (1.5), are presented in two tables. The first, Table (A.4), reports the change in aggregate emissions intensity due to survivors, entrants, and exiting establishments, and their sum from 1991 to 2006. The decline documented from year to year in the total due to all establishments, of course, corresponds to the aggregate changes in emissions intensity that can be seen from year to year in Figure (A.6). The annual changes reported are in scale-independent terms and can be interpreted as percentage point changes. The second, Table (A.5), reports the within- and between-establishment components for surviving establishments.

Examining the contribution of each channel in Table (A.4), several trends emerge. First, changes among surviving establishments are the most significant factor driving observed declines in aggregate emissions intensity and the sign always correlates with the aggregate change. To get a sense of the relative importance of each channel I computed the mean of the absolute value of each column. Survivors average 12.96, entrants average 2.13, and exiters average 4.78. Thus, as a share, survivors come in at 0.65,[23] entrants at 0.11, and exiters at 0.24, suggesting that, over the sample, the contribution of survivors is roughly five-times that of entrants, and nearly three-times that of exiters. Second, entering establishments are almost always cleaner than the average incumbent establishments–the only exceptions being 2001 and 2006. Third, exiting establishments are also almost always cleaner than the establishments they leave behind–the only exceptions being 2004 and 2006.[24] While potentially surprising, it is worth keeping in mind that exiting establishments are more likely to be young, and thus represent many of the relatively clean establishments that entered in the previous couple of periods. Finally, The declines in aggregate emissions intensity appear to be slowing in the last few years, relative to the declines documented from 1991 to 2001.

Extending the previous results, Table (A.5) breaks down the substantial contribution of surviving establishments into a within- and across-establishment component, in each year, based on the second line of equation (1.2). The second column just re-reports the total annual percentage-point change due to survivors, and columns three and four report the

[22] This analysis drops data from 1990 and 2006 since 100 percent of the establishments in those periods are entrants, or exiters (respectively).

[23] Survivors: $\frac{12.96}{12.96+2.13+4.78} \approx 0.65$

[24] Recall from equation (1.2) that exiting establishments will contribute to a decline in aggregate emissions intensity if exiting establishments have a higher emissions intensity than the establishments they leave behind.

decomposition of this change into the change due to within-establishment adjustment in production techniques and emissions intensities, and the change due to across-establishment reallocation of resources. The final two columns just report the same changes, divided by the sum of the absolute value of the within- and between-establishment components to turn the values into shares whose absolute values sum to 100, to provide an additional means of comparing the relative magnitudes of these two channels.

Although aggregate emissions intensity, through the survivors channel, declines in almost every period, whether that decline is largely driven by within-establishment adjustment or across-establishment reallocation varies substantially. In some periods the decline is driven by both channels, in some periods the two channels are working in opposite directions. A priori, there is little theoretical reason to expect one of these channels to be more important than the other. Over the entire period, though, the average of the absolute values of the within-establishment channel is 20.9, which is roughly an average of 7.4 percent per year larger than the average of the absolute value of the across-establishment channel at 19.4. The results thus suggest that, on average, the within-establishment channel are more important than reallocation across establishments, in driving observed changes in aggregate emissions intensity.

1.4 Robustness

Two of the assumptions employed in the previous analysis deserve additional attention. The first concerns my definition of entry and exit, and the second concerns my choice of establishment weights. As discussed above, I defined entry and exit by entry and exit from the RSEI database, which could be due merely to administrative exit from the sample, and not complete exit from the market. My comparison of entry and exit rates in the matched sample with those documented by the US Census shows that while this is likely the case, it may not be a significant problem. In addition, because I am using two separate establishment-level data sets, I am presented with the option of using an entry and exit identifier in the NETS database as well.[25] Using the NETS "firstyear" and "lastyear" indicators, establishments will not be flagged as exiting just because they leave the matched sample.

Using the NETS entry and exit flags, I report market shares by entering and exiting establishments, as well as entry and exit rates in Table (A.6). Comparing these results to those using the original definition as well as the US Census rates, in Table (A.3), reveals that

[25] As discussed above, the NETS database tracks establishment entry and exit with comparable accuracy to the US Census, however, as discussed in the sample comparison, large establishments appear to be over-represented in the matched RSEI-NETS sub-sample which may mean that entry and exit using this definition are lower than actual aggregate entry and exit rates.

entrants and exiters represent smaller market share, and have significantly lower entry and exit rates, as expected. I also plot the exit rate by establishment-age in Figure (A.8). While showing a general downward trend between establishment age and exit rates, the relationship is not as smooth as that plotted in Figure (A.8).[26] Finally, I re-do the decomposition based on the first line of equation (1.2), and report the results in Table (A.7). Comparing the results to those originally reported in Table (A.4) shows that the same basic story emerges. The primary differences are that entering and exiting establishments contribute even less to the overall declines in aggregate emissions intensity, exiting establishments are more likely to be dirtier and entering establishments a little less likely to be cleaner.[27] Of course, the total changes in aggregate emissions intensity for each period are the same, since differences in the choice of entry and exit definitions only affect the decomposition of the overall effect in each period. Neither of the definitions is ideal, the first using entry and exit from RSEI appearing to slightly overstate the degree of entry and exit, the second, using NETS, appearing to understate the degree of entry and exit. The truth likely lies somewhere in between. In both cases, however, the primary message is maintained: changes in aggregate emissions intensity are driven by reallocation of resources across surviving, entering, and exiting establishments, and the majority of the observed changes in aggregate emissions intensity are driven by surviving establishments.

The second concern to address is the choice of establishment weights. First, as discussed by Melitz and Polanec (2015), there is no theoretical reason to prefer one establishment-weighting scheme over another when focusing on changes in aggregate productivity. The same is basically true in my case as well, however with one important caveat. As laid out in equation (1.1), aggregate emissions intensity is just one component driving aggregate emissions, which is my ultimate concern. Thus, to link my decomposition of aggregate emissions intensity back to this original decomposition requires that I maintain the same output-weighting approach. Laying this consideration aside, though, there is no other reason to prefer output shares as weights in an analysis of aggregate emissions intensity, in isolation. Further, as documented by Foster et al. (2001), the choice of different weighting approaches is known to generate different conclusions regarding the channels driving employment, productivity and various other outcomes studied in related literature–it would thus, not be surprising if different choices of weights generated different conclusions in an analysis of aggregate emissions intensity. To explore this possibility I compare the trend in weighted-aggregate emissions intensity using four different establishment-level weights–nominal sales,

[26]This slightly noisier relationship is due, in part, to a relatively smaller share of establishments being documented as exiters.

[27]A larger share of the periods for entering establishments are positive, and a larger share of the periods for exiting establishments are negative, relative to the results reported in Table (A.4).

employment, emissions, and emissions intensity–and compare them to the baseline results presented in Figure (A.6).[28]

Figure (A.9) shows the annual trend in aggregate emissions intensity for each of the four alternative weighting options, compared to the baseline results. Using real output shares (the baseline case) gives more weight to larger, more productive establishments. Using employment shares, instead, for example, gives more weight to larger, but not necessarily more productive, establishments. Examining the panels in the first row of of Figure (A.9) shows a similar decline and flattening beginning around 2000 but the declines are not as strong as those obtained using output weights. This suggests that the decline in aggregate emissions through the aggregate emissions intensity channel is driven by larger and more productive establishments, and implies that nominal sales and employment data do not completely correlate with productivity and output.[29] Using emissions and emissions intensity shares gives more weight to dirtier establishments. With this approach, presented in the bottom two panels of Figure (A.9), aggregate emissions intensity appears to be flat or slightly increasing over the sample period, suggesting that the decline in emissions may not be concentrated among the dirtiest establishments.

Alternative weighting approaches do appear to yield fruitful insights into the channels driving aggregate emissions intensity. However, the ability to link the results smoothly to an intuitive decomposition of aggregate emissions, to better understand the establishment-level effects driving aggregate changes leaves my preference for the output-weighting approach unchanged.

1.5 Conclusion

In this paper I extend a decomposition proposed by Melitz and Polanec (2015) to show how establishment-level resource reallocation among entrants, exiters, and survivors, as well as within-establishment adjustments to production techniques contribute to changes in aggregate emissions through changes in aggregate emissions intensity. The decomposition neatly extends existing approaches in related environmental literature that decompose aggregate emissions into scale, composition, and aggregate technique effects. In my empirical analysis I show that both within and across sector channels are important channels driving observed changes in aggregate emissions, but that within-sector changes to aggregate emissions intensity are the most important channel. I further show that reallocation

[28] Sales and employment data are taken from the NETS database, emissions come from the RSEI database, and emissions intensities are calculated as the ratio of emissions to real output for each establishment.

[29] This is consistent with cross-country evidence presented by Bartelsman et al. (2013) showing that there is substantial variation in the strength of the correlation between firm productivity and size over time.

of resources between entering, exiting, and surviving establishments are each important channels driving observed changed in aggregate emissions, but that changes among survivors are the most important component. Among survivors, reallocation towards more efficient lower-emissions intense establishments, and within-establishment reductions in emissions intensity appear to be of similar importance.

While my within-sector analysis focused on the manufacturing sector as a whole, the decomposition approach I employed is actually quite flexible. As along as establishments don't change industry affiliation, the decomposition can be applied at any level of industry aggregation. Defining industries, instead, at the four-digit SIC level or any other interesting establishment group dimension and comparing results across groups would be a fruitful application of this technique.

The results presented here expose three key insights for those interested in efficient policy evaluation and design. First, the results show that when aggregate emissions are the outcome of interest, research needs to consider how policy changes affect both resource reallocation and technology upgrading and retrofitting among surviving firms, who account for roughly 65 percent of observed changes in emissions over the sample period. In addition, policy evaluation should consider the effects on entry and exit of polluting establishments which account for a small, though still substantial, 35 percent of observed changes in aggregate emissions intensity. Second, the results highlight the need for updated data gathering requirements. To accurately understand how policy changes affect aggregate emissions outcomes through reallocation of resources among survivors, entrants, and exiters, requires accurate data on the emissions of entrants, and exiters. Practically, this implies that the EPA should substantially lower the threshold reporting requirements for all chemicals tracked in the TRI, not just those that are highly toxic, like dioxin. Finally, the results showing the importance of resource reallocation among survivors, entrants, and exiters, provides a caution for policy makers to carefully consider the competitive effects of policy changes and regulation. As identified in related heterogeneous firm literature, for example, whether the regulatory costs come in the form of a higher fixed cost or a higher variable cost has important implications for employment and output effects of the policy change that should be carefully considered by anyone concerned with national welfare.

Chapter 2

The Environmental Effects of Trade Within and Across Sectors

2.1 Introduction

While imports to and exports from the US have risen nearly tenfold since 1980,[1] air borne emissions have declined by over 60 percent.[2] Historically, the literature that has studied the effect of increased trade on the environment has focused on either cross-sector comparative advantage, or, more recently, on within-sector adjustments due to heterogeneous firm responses. This paper addresses the question, how does trade affect the environment when across and within-sector channels are both at work and interacting?

To answer this question I extend a standard neoclassical two-sector model to include fixed costs and heterogeneous firms with free entry, while allowing firms to endogenously adjust their abatement investments in response to more stringent environmental policy. The resulting combined framework includes elements from a trade and environment framework developed by Copeland and Taylor (2003) as well as a two-sector heterogeneous firm model developed by Bernard et al. (2007b). The combined framework allows me to examine the environmental effects of changing trade costs as well as environmental policy both within and across sectors.

After showing that a stable equilibrium exists under autarky and free trade, I evaluate the model in the absence of trade, highlighting implications for environmental policy of the interaction of comparative advantage, fixed costs, and heterogeneous firms. Next I consider an autarky-to-free-trade experiment, emphasizing the comparative advantage role of factor endowments, environmental policy, fixed costs and heterogeneous firms. I conclude the theory by examining the model under costly trade–when firms face an additional fixed cost of exporting–to highlight the environmental effect of policy changes when both cross-sector as well as within-sector channels are operating.

The theoretical results have several implications for existing literature. First, my analysis under autarky contributes to a more general debate concerning the role of environmental policy in driving emissions reductions. The combined framework emphasizes the role that environmental policy can play both in affecting firms' intensive decisions regarding output and production techniques, but also their extensive decision regarding whether to enter or exit a market. Recent work by Restuccia and Rogerson (2013) summarizes a growing literature focusing on the implications of firm heterogeneity on policy efficiency with regard to various aggregate outcomes related to output, productivity, employment, and welfare. Empirical work focused on the environmental effect of firm heterogeneity by Becker et al. (2013b), Greenstone et al. (2012), and Heutel (2011) has shown that environmental

[1] US Census Trade in Goods and Services, June 3, 2015

[2] EPA (US Environmental Protection Agency Air Quality Report, 2012)

policy may have different effects across firms and emphasizes the potentially important role of environmental policy as a fixed cost that influences firms' output, productivity, and abatement decisions, but these studies generally do not address the general equilibrium effects of firm entry and exit. Recent papers by Tombe and Winter (2015), Li and Sun (2015), Tang et al. (2014), and Holland (2012) evaluate the implications for various types of environmental policy in a single sector model with heterogeneous firms. In contrast to the combined framework, these recent papers ignore the role of endowments, fixed costs, and environmental policy influencing cross-sector movement of resources. In the appendix I describe and present results from a decomposition of establishment emissions from the National Emissions Inventory, that provides additional evidence that variation in emissions outcomes within- and across-sectors are both important, further motivating the need for a framework to combine both channels.

Under the common simplifying assumption that fixed costs of production and entry require the same input ratios, the combined framework shows that more stringent environmental policy induces firms to choose a lower emissions intensity, as in related representative-firm models developed in McAusland and Millimet (2013) and Antweiler et al. (2001). However, when this knife-edge assumption is relaxed, for example to consider the case when fixed investments required for production do not entail any emissions, environmental policy induces an additional effect on firms' entry and exit decision. In this case, more stringent environmental policy raises a barrier to entry that insulates incumbent producers and allows lower-productivity, more emissions-intense producers to profitably remain in the market. This extensive margin response to more stringent environmental policy results in lower average productivity and higher sector emissions intensity.[3] This implies that environmental policy design and evaluation should carefully account for both intensive margin adjustment to production techniques as well as the presence and effect of fixed costs influencing firm selection in and out of the market. The combined framework emphasizes the point that when environmental policy induces significant firm entry or exit, environmental regulation–influencing both cross-sector as well as within-sector adjustment–has additional implications for job creation and overall welfare beyond the direct environmental effects.

Second, my analysis under free trade and costly trade reveals contributions for the existing trade and environment literature. In the analysis of the free-trade equilibrium, the combined framework shows that when factor allocations in a sector are not fixed but are free to move between sectors, trade liberalization can result in cross-sector resource movement according to the country's comparative advantage. Recent work by Kreickemeier

[3]This reallocation affect is reversed in the case when fixed production requirements entail a larger environmental effect relative to entry.

and Richter (2013) develops a single-sector heterogeneous firm model showing that when productivity is emissions augmenting, endogenous productivity gains can reduce emissions intensity and result in overall environmental improvements, while Holladay (2016); Cui et al. (2015); Forslid et al. (2011) present empirical evidence that increased trade can lead to emissions intensity reductions. In related work, Shapiro and Walker (2015) present empirical evidence attributing much of the recent reduction in US manufacturing to implicit changes in environmental policy. This recent literature has tended to focus both theory and empirical research on the means by which trade or environmental policy–in the context of a single sector comprised of heterogeneous firms facing fixed costs–can induce endogenous reductions in emissions intensity. In contrast to this single-sector literature, the combined framework shows that trade liberalization will tend to correspond with greater emissions demand when a country holds a comparative advantage in capital intense, dirty production, even while productivity rises and aggregate emissions intensity declines. Researchers and policy makers alike, concerned with the overall level of emissions should not take emissions intensity reductions to imply that total emissions are declining.

My analysis of the costly trade equilibrium reveals insights for the literature developed around a neoclassical two-sector framework. This literature, including work by Copeland and Taylor (1994), Antweiler et al. (2001), and Cole and Elliott (2003), tends to emphasize the role of cross-sector comparative advantage stemming from differences in endowments or environmental policy, in driving the environmental effects of trade, and the role of environmental policy in offsetting potential negative environmental effects. The combined framework extends this literature by showing that when trade is costly–in particular when firms face fixed costs of entry, production, and export–and firms differ in their productivity levels, a reduction in trade costs results in endogenous productivity gains that lower aggregate emissions intensity, even when the relative stringency of environmental policy is left unchanged. This result stems from increased competition that ensues as firms seek to serve the foreign market and bid for a finite set of inputs, ultimately resulting in the shrinking and exit of the least productive and most emissions intense firms.

Building on early work by Grossman and Krueger (1994) and Grossman and Krueger (1995), existing literature conventionally decomposes changes in emissions into three sources: changes in the size of the broader economy ("scale"), changes in the relative share of inputs and output allocated across sectors ("composition"), and changes in production techniques affecting emissions intensity ("technique"). Following this convention, I show that, when across and within sector influences are incorporated into a combined framework, endogenous productivity gains due to within-sector reallocation across firms affect each of the scale, composition, and technique effects, relative to a representative firm model. In particular, the

scale effect will be larger as productivity gains across all sectors lead to output growth, and the negative technique effect will also be strengthened as endogenous productivity gains lower emissions intensity in the polluting sector. The composition effect will be muted, though not reversed, as some of the rise in relative demand is served through relative increases in productivity as opposed to shifting resources across sectors. This is a key result that provides a potential explanation for recent empirical evidence of large scale and technique effects, but relatively small composition effects in both Antweiler et al. (2001) and Levinson (2009).

In addition, the neoclassical framework employed by Copeland and Taylor (2003) shows how efficient environmental policy will be required for trade liberalization to correspond with overall environmental improvement when the home country holds a comparative advantage in relatively dirty production. The combined framework extends their result by showing that, in addition to accounting for consumer preferences and the country's comparative advantage relative to the trading partner, the design of efficient regulation must also account for the endogenous reduction in a polluting sector's emissions intensity that arises as emissions intense firms exit the market.

This paper shows that accounting for the presence of fixed costs, a distribution of heterogeneous productivity across firms, and their interaction with comparative advantage effects across sectors is key to understanding the means by which policy changes and market characteristics affect our environment. These effects and interactions are of particular importance for those concerned with the efficient design of environmental policy whether following, or in anticipation of, a trade liberalization.

2.2 Setup

In this section I develop a two-sector, two-input trade and environment framework with heterogeneous firms, fixed costs, and environmental policy. The framework combines elements of Copeland and Taylor (2003) and Bernard et al. (2007b).

2.2.1 Demand

I consider an international setting with two trading partners, home and foreign or rest-of-world, $n \in \{H, F\}$, both home to a continuum of heterogeneous firms each of which produces a differentiated variety in one of two sectors, $s \in \{1, 2\}$.[4] Consumers enjoy consumption, C, of differentiated varieties, $\omega \in \Omega$, produced in both sectors. For simplicity I assume consumer

[4]To focus on the comparative-advantage role of factor endowments, I make the assumption that the two trading partners have the same technology, but differ in their relative factor endowments of capital and labor.

utility to be aggregated across sectors in a Cobb-Douglas fashion. Firms produce with capital and labor and the home country is capital abundant relative to the foreign trading partner, so that $\bar{K}^H/\bar{L}^H > \bar{K}^F/\bar{L}^F$, where bars indicate the trading partner's endowments:[5]

$$\underset{C_1,C_2}{U} = C_1^{\eta_1} C_2^{\eta_2}, \qquad \eta_1 + \eta_2 = 1, \quad \eta_1 = \eta \tag{2.1}$$

Consumption and a corresponding price index in each sector are both defined over varieties in a standard CES form:

$$C_s = \left[\int_{\omega \in \Omega} q_s(\omega)^{\rho} \, \mathrm{d}\omega \right]^{\frac{1}{\rho}}, \qquad P_s = \left[\int_{\omega \in \Omega} p_s(\omega)^{(1-\sigma)} \, \mathrm{d}\omega \right]^{\frac{1}{(1-\sigma)}} \tag{2.2}$$

where $\sigma > 1$ captures consumers' elasticity of substitution between varieties, and $\rho \equiv \frac{\sigma-1}{\sigma}$. Using the consumer utility and price index defined above, consumer inverse demands for individual varieties in a given sector are given by:

$$q_s(\omega) = \eta_s R P_s^{\sigma-1} p_s(\omega)^{-\sigma} \tag{2.3}$$

where R represents aggregate expenditure, of which η_s represents the share of their income that consumers spend on sector s. Thus, $\eta_s R = R_s$ can be used interchangeably, where R_s is simply total sector revenue.

2.2.2 Production

The production setup draws on Copeland and Taylor (2003), the important difference being that I relax their assumption that firms are homogeneous with respect to their productivity levels. A firm's gross or potential production, y, requires capital and labor:

$$y_s(\varphi, k, l) = \varphi l^{1-\beta_s} k^{\beta_s} \tag{2.4}$$

where the productivity parameter, φ, is firm-specific. Additionally, production may result in a firm releasing emissions, z. Firms have access to an emissions-reducing abatement technology that exhibits decreasing returns. Similarly to Copeland and Taylor (2003), though with the addition of a firm-specific productivity component, I assume a specific abatement

[5] Throughout the model, capital letters will denote aggregate variables, while lowercase letters denote firm-level variables.

function, and emissions released per-unit of gross output, Λ_s, is given by:

$$\Lambda_s(\theta_s) \equiv \frac{(1-\theta_s)^{1/\alpha_s}}{\varphi} \tag{2.5}$$

where the exogenous parameter α_s has support (0,1). A lower α_s represents an increase in the cost effectiveness or efficiency of available abatement technology or a lower per-unit emissions requirement for a firm in a given sector. The variable $\theta_s \in [0,1]$ represents the share of a firm's output that they choose to devote to abatement. If emissions are taxed a firm may choose to reallocate some of their resources to increase their investment in abatement which reduces emissions as Λ_s declines.

Using (2.5) the net-output of a firm in a given sector, q_s (net of the share of resources devoted to abatement), can be written equivalently as a function of capital and labor inputs and the firm's abatement share choice, θ_s, or as a function of three inputs: capital, labor, and emissions.

$$\begin{aligned} q_s &\equiv (1-\theta_s) y_s(\cdot) \\ q_s &= \varphi z_s^{\alpha_s} (k_s^{\beta_s} l_s^{1-\beta_s})^{1-\alpha_s} \quad , \quad 1 > \beta_1 > \beta_2 > 0 \end{aligned} \tag{2.6}$$

Consistent with recent empirical literature, I assume that sector one is capital intense and emissions intense relative to sector two.[6] To simplify the following analysis I assume that only firms in sector one emit pollution (i.e. $\alpha_2 = 0$).

Cost Minimization

Following the literature on heterogeneous firms I assume that production also requires a fixed investment, f_s, common to all firms in a sector that has the same unit input requirements as variable production, an aspect absent from representative-firm models. The cost minimizing input bundle involves an abatement choice regarding the amount of capital and labor that a firm will devote to output relative to the amount they will devote to abatement, which in turn implies a choice of how much emissions to generate relative to capital and labor. A given firm's cost-minimizing choices of k, l, and z in the net-output setup from (2.6) yields the following production cost function :

$$\Gamma_s \quad = \quad \left(\frac{q_s}{\varphi} + f_s\right) \frac{w^{1-\beta_s} i^{\beta_s} \nu_s}{(1-\alpha_s)(1-\theta_s)} \tag{2.7}$$

[6] See Kahn (1999); Cole et al. (2005); Cole and Elliott (2005)

where w and i capture wages and rents, and $\nu_s = (1-\beta_s)^{\beta_s - 1}\beta_s^{-\beta_s}$. A firm's optimal choice of abatement share, θ_s, is the cost-minimizing solution to their choice concerning the amount of capital and labor to devote to net output relative to the amount to devote to abatement:[7]

$$(1-\theta_s) = \left(\frac{w^{1-\beta_s} i^{\beta_s} \nu_s}{t_s} \frac{\alpha_s}{1-\alpha_s} \right)^{\alpha_s} \tag{2.8}$$

where t_s represent a per-unit-of-emissions tax that is given exogenously.[8]

For a firm that chooses not to devote any of their capital and labor resources to investments in abatement, their net output is equal to their gross, i.e. $q_s(\cdot) = y_s(\cdot)$ and, for polluting firms in sector one, no abatement investment means that each unit of output results in a unit of emissions released: $z_1 = y_1(\cdot)$. As firms devote more resources to abatement, net output falls, and in the extreme, as θ_s approaches one, net-output (and thus revenue), approaches zero, and the firm will exit the market. In the following analysis I focus on the case when the emissions tax is high enough that firms choose to invest in some abatement, but low enough to allow some firms to continue in the market. Finally, it is worth noting that firms within the same industry do not differ in their optimal choice of abatement share, since $(1-\theta_s)$ is independent of individual productivity, and thus a firm's choice of emissions relative to their capital and labor inputs is only a function of technology parameters and relative factor prices. This feature of the model, though not addressed in further detail here, is supported by plant-level analysis in Shadbegian and Gray (2005) who find no significant difference in the marginal abatement costs across different plant types within the same industry.[9]

Profits and Pricing

The market is characterized by monopolistic competition. Firms wishing to enter the market and begin producing must sink a sector-specific fixed entry cost, f_{es}, which I assume has same unit input requirement as the fixed production cost, and draw a unique productivity

[7] Formally, the firm solves: $cost^{q_s}(w,\, i,\, t_s) = \min_{z_s,\, y_s} \{ t_s \cdot z_s + cost^{y_s} \cdot y_s \,:\, (\varphi z)^{\alpha_s} y_s^{1-\alpha_s} = 1 \}$.

[8] The current model abstracts away from the political-economy model that generates emissions taxes, and firms take the emissions tax as exogenously given. Though allowing for endogenous policy determination is feasible (see Copeland and Taylor (2003) for an example) the change in emissions demand in response to more stringent environmental policy are relatively straightforward, while the means by which the emissions tax might change hinge, importantly, on the particular political-economy model employed. In addition, my use of CES preferences means that consumer utility increases one for one with real income, and thus the marginal damages of emissions are not affected by changes in real income and are only a function of output prices (a substitution channel) and consumer preferences for a cleaner environment.

[9] This is in contrast to the single sector models developed by Kreickemeier and Richter (2013) and Tang et al. (2014) who define firm's emissions per unit of labor as a declining function of the firm's productivity level. To my knowledge the relative empirical implications of these two modeling choices has not been examined elsewhere in the literature.

level from the distribution $G(\varphi)$. Due to this requirement, and the CES demand structure combined with the presence of fixed production costs, each variety will be produced by a single firm (and each firm will produce a single variety), and thus both firms and varieties can be indexed by their productivity level, φ.

In a monopolistically competitive market where consumers love variety, firms have some power to set prices above their marginal cost[10] and profit maximization yields the following price-setting rule:

$$p_s(\varphi) = \frac{w^{1-\beta_s} i^{\beta_s} \nu_s}{\varphi \cdot \rho \cdot (1-\theta_s)(1-\alpha_s)} \tag{2.9}$$

where a firm's optimal price is merely a constant markup over its marginal cost. This is the price the producer receives after paying emissions taxes and abatement costs .

Combining this pricing rule with consumer's inverse demands from (2.3), a firm's revenue and profits can be written as:

$$\begin{aligned} r_s(\varphi) &= \eta_s R P_s^{\sigma-1} p_s(\varphi)^{1-\sigma} \\ \pi_s(\varphi) &= \frac{r_s(\varphi)}{\sigma} - f_s \frac{w^{1-\beta_s} i^{\beta_s} \nu_s}{(1-\alpha_s)(1-\theta_s)} \end{aligned} \tag{2.10}$$

The firm's pricing rule implies that the relative revenue of two firms within the same sector and market and with access to the same abatement technology depends solely on their relative productivity: $\frac{r(\varphi')}{r(\varphi'')} = \left(\frac{\varphi'}{\varphi''}\right)^{(\sigma-1)}$.

A zero-profit condition identifies the productivity cutoff, φ_s^*, in each sector:

$$r_s(\varphi_s^*) = \sigma f_s \frac{w^{1-\beta_s} i^{\beta_s} \nu_s}{(1-\alpha_s)(1-\theta_s)} \tag{2.11}$$

the difference from Bernard et al. (2007b) being the additional consideration of the firm's abatement choice, θ_s. As the relative stringency of environmental policy rises, firms will divert resources away from net output and towards abatement, thus reducing revenues and raising the productivity cut-off.

Equilibrium in each market implies that average revenue and profits are equal to the revenue and profits of a firm with an average productivity draw: $\bar{r}_s = r_s(\tilde{\varphi}_s)$ and $\bar{\pi}_s = \pi_s(\tilde{\varphi}_s)$. Average productivity in a sector, $\tilde{\varphi}_s$ is an output-weighted average across all firms that draw

[10] As demonstrated in Baldwin et al. (2005) p. 40 when the number of firms/varieties grows large (approaching infinity) as in the present monopolistically competitive case with an unbounded fringe of potential entrants, consumers' price elasticity of substitution equals σ whether firms are competing on price or on quantity and firms can be thought of equivalently as choosing prices or quantities.

a productivity above the zero-profit cutoff.[11] This average is monotonically increasing in the productivity cutoff, φ_s^*, and captures the means by which endogenous changes in the productivity cut-off affect output, revenue, prices, and profits.

This average can be used to rewrite the aggregate price index and output level for a given sector from (2.2) and (2.3) as (See Appendix):

$$\begin{aligned} P_s &= M_s^{\frac{1}{1-\sigma}} p(\tilde{\varphi}_s) \\ Q_s &= M_s^{1/\rho} q_s(\tilde{\varphi}_s) \end{aligned} \tag{2.12}$$

where the aggregate values are defined across firms that are actually present in the market sector via $\tilde{\varphi}_s$, and M_s is the mass of firms[12] operating in a given sector.

Free Entry

Firms entering the market must cover the fixed cost of entry, f_{es}, and then face the continuous potential of a negative economic shock that forces them to shutdown, δ. The expected value of entry for a firm a particular sector depends on the probability of successful entry, and the expected profits in the sector. With an unbounded fringe of potential entrants, firms will continue to enter the market until the expected benefits of entry, V_s, reach zero. The free entry condition is thus:

$$V_s = \frac{[1 - G(\varphi_s^*)] \cdot \bar{\pi}_s}{\delta} = f_{es} \frac{w^{1-\beta_s} i^{\beta_s} \nu_s}{(1-\alpha_s)(1-\theta_s)} \tag{2.13}$$

where $[1 - G(\varphi_s^*)]$ represents the probability of successful entry.

The combination of the free-entry condition and the zero-profit condition creates a series of two equations linking φ and $\bar{\pi}$ which identify φ_s^* as only a function of fixed costs and model parameters. Just as in Bernard et al. (2007b), the free-entry condition completely pins down φ_s^* independent of factor rewards and other endogenous model variables:

$$V_s = \frac{f_s}{\delta} \int_{\varphi_s^*}^{\infty} \left[\left(\frac{\varphi}{\varphi_s^*} \right)^{(\sigma-1)} - 1 \right] g(\varphi) \mathrm{d}\varphi = f_{es} \tag{2.14}$$

where $g(\varphi)$ is the ex-ante productivity distribution.

[11] See Appendix.

[12] For expositional convenience the reader may refer to M_s as the number instead of mass of firms without loss of generality.

The value of entry is decreasing in the shutdown probability, δ, and increasing in the fixed costs of production. A higher rate of firm failure lowers the mass of incumbent firms and raises the probability drawing a productivity high enough to cover the costs of entry, lowering the productivity cut-off. Higher fixed costs of production imply that firms must draw a higher productivity to profitably serve the market.

Goods and Factor Markets

In the steady state equilibrium, the mass of firms exiting due to adverse shocks is equal to the mass of entering firms,

$$\delta M_s = [1 - G(\varphi_s^*)] \cdot M_{es} \tag{2.15}$$

Firm entry and exit in any given sector does not affect the equilibrium zero-profit productivity cut-off or sector averages because δ is exogenous, and thus the distribution of firms entering is equal to the distribution of firms exiting the market.

Capital and labor that firms use for production and entry must clear their respective markets:

$$\begin{aligned} \bar{K} = K_1 + K_2, \quad K_s = K_s^p + K_s^e \\ \bar{L} = L_1 + L_2, \quad L_s = L_s^p + L_s^e \end{aligned} \tag{2.16}$$

where $\bar{K}$ and $\bar{L}$ denote the available supply of capital and labor (respectively), as determined by a country's factor endowments. The superscript p refers to factor demands for production, and the superscript e refers to entry requirements.

With a continuum of firms and products, and multiple sectors, the free entry and full employment conditions completely pin down factor prices according to the marginal productivity of the factors in the different sectors.

2.2.3 Integrated and free-trade equilibria

I first solve for the equilibrium in the world integrated economy in which goods *and* factors of production are mobile, as is the case *within* a country under complete autarky. I then show that the free-trade equilibrium, when only goods (and not factors) are mobile, replicates resource allocation of the integrated economy, as determined by relative prices.

The equilibrium is referenced by a vector of ten variables: $[\varphi_s^*, P_s, R, p_s(\varphi), w, i, t_1]$, $s \in \{1, 2\}$ in which φ_s^* is pinned down by the zero-profit condition and the free-entry condition. Factor prices w and i are determined by factor market clearing conditions and free-entry, and t_1 is exogenous. Aggregate prices and revenues are functions of average firm

productivity, factor prices, and φ_s^*. I assume in this scenario that trading partner's factor endowments are sufficiently similar such that factor prices equalize.

Proposition 1. *There exists a unique integrated equilibrium characterized by the vector* $\{\varphi_s^*, P_s, R, p_s(\varphi), w, i, t_s\}$, $s \in \{1, 2\}$. *Under free trade, there exists an allocation of global factor endowments such that the unique free trade equilibrium replicates the resource allocation of the integrated world economy via equilibrium factor returns and prices.*

Proof: See Appendix.

The autarky or integrated equilibrium provides the foundation for the rest of the analysis regarding the role of trade policy in determining environmental outcomes and allows me to compare predictions and comparative statics results to those obtained in other models and frameworks. The inclusion of the endogenous emissions component, in addition to capital and labor allocations, is addressed by relying on the recursive nature of the production structure, as in Copeland and Taylor (2003). Individual firms take the emissions tax as given, and output, capital and labor allocations, and other endogenous variables can thus be solved for in equilibrium independent of the emissions level. Per-unit emissions are identified as a relationship between these equilibrium values and the emissions tax. Total emissions can then be determined by scaling average per-unit emission by the equilibrium level of output in the polluting sector. Other equilibrium variables are solved as in Bernard et al. (2007b). I turn next to emissions demand and the role of trade policy in determining emissions outcomes.

2.2.4 Emissions Demand

To highlight the different contributions of the combined framework, I first analyze firm-level emissions demands, and then aggregate those to analyze cross-sector demands.

Firm-level Emissions

Using the firm profit function in (2.10), the unconditional demand for emissions emitted in the course of production by a firm in sector one is given by:

$$z_1^p(\varphi) = \frac{\alpha_1}{t_1}\left[r(\varphi)\cdot\rho + f_1\frac{w^{1-\beta_1}i^{\beta_1}\nu_1}{(1-\alpha_1)(1-\theta_1)}\right] \tag{2.17}$$

where the first term in brackets captures what the firm spends on emissions generated in variable production, and the second term captures fixed environmental expenditures. Both of these features have known corollaries in current manufacturing practices. For example, continuous disposal, monitoring, reporting, and containment costs represent a marginal cost of emissions that firms face while investments in more efficient "control technology" for the express purpose of reducing emissions are other fixed environmental production costs that firms undertake–often to comply with environmental regulation and permit requirements–that provide services over time.[13]

Using (2.11) and the revenue relationship between two different firms in a given industry and (2.8),[14] a firm's equilibrium emissions demand simplify to

$$z_1^p(\varphi) = \left[(\sigma-1)\left(\frac{\varphi}{\varphi_1^*}\right)^{\sigma-1}+1\right] f_1 \cdot (1-\theta_1)^{(1-\alpha_1)/\alpha_1} \tag{2.18}$$

A polluting firm's demand for emissions, z_1, decreases in response to a higher emissions tax, t_1, relative to the costs of capital and labor (which raises the share of resources they choose to divert to abatement, θ_1), or an increase in the efficiency of available abatement technology (i.e. α_1 falls). A rise in the sector productivity cut-off lowers a given firm's emissions demand because a higher productivity cut-off corresponds with higher average profits, and thus additional resources (including emissions) are bid away as more firms seek to enter the market. A firm's emissions demand rises with their fixed costs, f_1.[15]In addition, more productive firms will also demand more total emissions than less productive firms in the same industry and country. More productive firms are able to lower their prices and increase their revenues and profits which in turn allows them to hire additional factors of production, including emissions. This does not imply, however, that industry wide productivity gains contribute to higher emissions demand. To address the total impact of a trade liberalization on emissions the model must also consider the effect of firm entry and exit induced by falling trade costs–a margin that is ignored in representative firm models. I turn now to aggregate firm-level emissions.

[13]For example Heutel (2011) and Greenstone (2002) discuss the role that environmental policy plays in determining firm's investment in abatement equipment. They show that environmental policy can effectively serve as a barrier to entry or new investment, by raising the costs of these activities, correlating to fixed costs in the present model.

[14]Note that $\frac{\alpha_1}{t} \cdot \frac{w^{1-\beta_1} i^{\beta_1} \nu_1}{(1-\alpha_1)(1-\theta_1)} = (1-\theta_1)^{(1-\alpha_1)/\alpha_1}$

[15]Rising fixed costs raise emissions demand for a firm, but also raise the productivity cut-off. The net effect of these changes is indeterminate without a stronger distributional assumption regarding $G(\varphi)$. If firm productivity is distributed Pareto, a finding supported by Axtell (2001), it can be shown that a rise in fixed costs unambiguously raises the emissions demand of an operating firm. See appendix.

Sector-level Emissions

Total emissions demand is the sum, across active firms, of total per-firm emissions due to production:

$$Z_1^p = \frac{1}{1 - G(\varphi_1^*)} \int_{\varphi_1^*}^{\infty} z_1(\varphi) M_s g(\varphi) \mathrm{d}\varphi \tag{2.19}$$

plus emissions due to entry.[16] Market clearing conditions then allow emissions demand in sector one to be written as a constant share of total sector revenue as:

$$Z_1 = Z_1^p + Z_1^e = \frac{\alpha_1 R_1}{t_1} \tag{2.20}$$

Recognizing that $R_s = Q_s \cdot P_s$, and using (2.12) and the pricing rule from (2.9), aggregate emissions demand can be further decomposed into the mass of firms, average output, and endogenous emissions intensity:

$$Z_1 = M_1 \bar{q}_1 \frac{(1 - \theta_1)^{(1-\alpha_1)/\alpha_1}}{\tilde{\varphi}_1 \rho} \tag{2.21}$$

In the combined framework, changes in trade costs can induce endogenous changes in average productivity and the mass of firms, due to firm entry and exit–margins that are absent in a representative firm framework–while the country's comparative advantage affects relative wages which drive factor allocations across sectors that work through the mass of firms. An increase in the mass of firms raises output and thus raises emissions demand as does a rise in average output, while the direct effect of a rise in average productivity reduces per-unit emissions and total emissions, other things equal. Finally, an increase in the share of resources devoted to abatement, θ_1–due to an increase in the emissions tax relative to the market determined capital and labor costs–reduces emissions demand.

2.3 Environmental Policy in the Combined Framework

Before evaluating the role of trade in the combined framework, it is worth emphasizing how the combined framework facilitates analysis of the role of environmental policy within and across sectors. First, increased environmental stringency raises the cost of emissions relative to other inputs. Firms respond by shifting resources away from production and increasing their investment in abatement, seen in (2.8), thereby reducing their emissions intensity. Second, other things equal, a rise in costs due to a higher emissions tax raises average prices

[16] See proof of *Proposition 1*, for emissions demand used during entry.

and the price index in the polluting sector, given in (2.30), thereby reducing the polluting sector's comparative advantage and resulting in the shift of resources into the clean sector.

Environmental policy is limited to these two effects under the assumption, common in heterogeneous firm models,[17] that entry and production use identical factor intensities. Empirical evidence in related environmental literature calls this assumption into question. Becker et al. (2013b) present evidence that market entrants may face additional environmental stringency, relative to incumbents. Theoretical and empirical work by Heutel (2011) shows that implementing different environmental stringency for new firms, relative to existing firms, for example as is the case for "grandfathering" provisions in the Clean Air Act Amendments, can result in unintended consequences in terms of firm's production and investment behavior. The combined framework presents a similar message, but working through an endogenous entry and exit of firms that influences aggregate productivity.[18] Consider a scenario in which entry does not involve the use of emissions, such that entry costs do not entail payment of an environmental tax and are instead given by, $f_{es}\left(\frac{w^{1-\beta_s} i^{\beta_s} \nu_s}{(1-\alpha_s)\cdot\alpha_s^{\alpha_s/(1-\alpha_s)}}\right)^{1-\alpha_s}$. In this case, the free-entry and zero profit conditions under autarky given in (D.3) become:

$$V_s = \frac{f_s \cdot t_s^{\alpha_s}}{\delta} \int_{\varphi_s^*}^{\infty} \left[\left(\frac{\varphi}{\varphi_s^*}\right)^{(\sigma-1)} - 1\right] g(\varphi)\mathrm{d}\varphi = f_{es} \tag{2.22}$$

and, in contrast with a representative firm model, changes in environmental regulation now also affect the productivity cut-off and influence reallocation of resources across firms and thus firm's entry and exit decision. In particular more stringent environmental policy raises production costs and raises the profits and productivity cut-off value that firms must have in order to remain in the market. Under this scenario, increases in environmental stringency serve to reduce emissions through a third, extensive margin, by driving the most emissions intense producers from the market. Intuitively, more stringent environmental policy raises the costs for operating firms. The presence of fixed costs means that they cannot pass all of these costs along to consumers in the form of markups, and the least productive firms suffer a revenue loss that forces them to exit. Note that this third effect would work in reverse if, instead, entry entailed more stringent environmental policy than production.

When entry and production are different types of activities, as in (2.22), more stringent environmental policy will raise productivity cut-off more when fixed production costs are high, or entry costs are low. In this case, productivity gains resulting from increased environmental stringency are higher in markets characterized by more entry: when fixed

[17] See examples in Hopenhayn (1992); Melitz (2003); Bernard et al. (2007b).

[18] Heutel (2011) doesn't consider the general equilibrium effects of entry and exit.

costs are higher, firms must earn higher profits to remain in the market and the resulting rise in average profits attracts more market entrants, while lower fixed entry costs lower barriers to entry and thus serve to raise the amount of entry. Indeed, absent a reduction in trade costs in this scenario under autarky, environmental regulation serves as the only policy mechanism in this framework that can readily affect productivity.[19]

2.3.1 Environmental dynamics

On the one hand, relaxing the seemingly strong assumption that entry and production use identical factor intensities does not significantly change the ultimate conclusion: environmental policy works to reallocate resources away from dirty production and reduces sector emissions intensity, however, the level of stringency required to achieve particular environmental goals does depend on these assumptions. When efficiency is a concern, the combined framework also shows that not all of the reductions in emissions intensity result from intra-firm choices regarding abatement investments, but they may also result from the exit of emissions intense producers and thereby entail job loss and resource reallocation across firms. In addition, building on Hopenhayn (1992), the combined framework emphasizes the point that the reallocation across firms driving changes in average productivity and emissions intensity will not be instantaneous. For example, if environmental policy raises the fixed entry cost that firms must cover, there will be less entry. However, because incumbent firms have already sunk that cost, the policy change primarily affects the characteristics of new entrants. Thus, the speed with which the within sector reallocation and resulting reduction in the productivity cut-off will follow depends on additional industry characteristics, like the rate of firm exit, δ. As this scenario shows, changes in environmental policy can induce changes within and across sectors that interact to influence total emissions demand, and that the effects of policy changes across firms will be contingent on the characteristics and competitiveness of the sector.

2.4 The Environmental Role of Comparative Advantage

I proceed to analyzing the environmental effects of changing trade costs by first considering the effects of a move from autarky to free trade. This experiment highlights the environmental role of comparative advantage in the combined framework. The opening

[19] The relationship between environmental policy and technology adoption is discussed in detail in Jaffe et al. (2002).

of trade leads relative prices to converge, but in the absence of fixed costs of exporting, several key margins influencing the heterogeneous response of firms are left unchanged.

Proposition 2. *In the move from autarky to free trade, there is no change in the productivity cut-off, φ_s^*, or average productivity, $\tilde{\varphi}_s$, in any sector and a country's emissions demand adjusts according to their comparative advantage:*

a) If the home country holds a comparative advantage in relatively dirty production, the move from autarky to free trade raises emissions demand, while emissions demand falls if it holds a comparative advantage in clean production, ceteris paribus.

b) If the country holds a comparative advantage in pollution intense production, the move from autarky to free trade lowers emissions only if the country experiences a strong simultaneous rise in the emissions tax and firms raise the share of resources devoted to abatement.

c) For a country holding a comparative advantage in relatively dirty production, the trade-induced rise in emissions is smaller when environmental policy is relatively more stringent or when the polluting sector faces lower fixed costs and has a higher productivity cut-off and average productivity level.

Proof: See Appendix

Under autarky, the relative abundance of capital in the home country leads to a lower relative price for capital and for the capital intense good, thus the home country holds a comparative advantage in dirty production as long as higher costs imposed by environmental regulation do not reverse the relationship between relative output prices between the trading partners. In the present combined framework the fact that the move from autarky to free trade leaves the sector cut-off productivity unchanged arises because all firms are affected in a similar manner. All firms are subject to foreign competition and all gain access to the foreign market. Although the switch to free trade does affect relative factor returns, in the absence of fixed trade costs, incumbent firms are able to pass any changes in input costs along to consumers. With identical factor intensities of production and entry, the changes to the cost of production and value of entry are symmetric, leaving the productivity cut-offs unchanged.[20]

To evaluate the role that trade plays in determining emissions demand, given in (2.20), I first assume that the relative stringency of environmental policy remains unchanged, such that θ_1 remains fixed. This is equivalent to assuming that individual firm's emissions intensity

[20] As in Melitz (2003), this result is due to the combination of CES preferences and the assumption that firms use the same factor intensity for fixed and variable production.

remains unchanged once they realize their specific productivity value.[21] Average firm output, given by $q(\tilde{\varphi}_s) = \left(\frac{\tilde{\varphi}_s}{\varphi_s^*}\right)^{\sigma} q_s^* = \left(\frac{\tilde{\varphi}_s}{\varphi_s^*}\right)^{\sigma} (\sigma - 1) f_s \varphi_s^*$, is pinned down by the productivity cutoff, and is therefore unchanged. Thus, in the absence of a change to the productivity cut-off and average productivity or firms' abatement investment share, falling trade costs only influence a country's emissions demand through changes in the mass of firms which are driven by relative output changes as resources shift across sectors according to the country's comparative advantage. As capital and labor move into the comparative advantage dirty sector at home, the mass of firms and varieties, M_1, rises while M_2 declines. The resulting rise in emissions demand in the home country would only be reversed if a corresponding rise in environmental stringency induced firms to substitute away from emissions, thus dampening sector one's comparative advantage as well as raising investment in abatement, θ_1. Still, even absent a change in the productivity cutoff, combined-framework reveals that the comparative advantage channel driving environmental outcomes through cross-sector movement of resources, interact with two factors influencing emissions intensity in the sector. In particular, a sector facing less stringent environmental policy will enjoy a greater comparative advantage and the cross-sector movement of resources will be magnified, while lower fixed costs will result in a higher productivity cut-off, seen in (D.3), and will also magnify the role of comparative advantage and cross-sector resource movement.

Proposition 2 highlights how differences in environmental policy and factor endowments influence emissions demand in this general equilibrium framework. The benchmark case–moving from autarky to free trade–essentially mirrors the costly-trade findings of Antweiler et al. (2001), but with the added insight that changes in cross-sector resource allocation that occur as relative wages change work by driving changes in the relative mass of firms as resources are attracted into the comparative advantage sector, and that the magnitude of the cross-sector adjustments are augmented by the presence of heterogeneous firms and fixed costs. The benchmark shows the environmental effects of a trade liberalization in the absence of fixed trade costs. However, fixed trade costs are known to be an important factor influencing firms export decisions,[22] and their inclusion generates within-sector differences in firm entry and exit into export markets which are a prevalent feature of international trade data.[23] I turn now to analyze the model under the assumption of costly trade.

[21] This type of emissions intensity target, along with several countries implementing such a policy regime, is discussed in Fischer and Springborn (2011).

[22] See Roberts and Tybout (1997a,b) for examples of the importance of fixed export costs determining firms' export decision.

[23] For examples see Bernard et al. (2007a)

2.5 Costly Trade

I now introduce notation for home and foreign variables when necessary, and distinguish between domestic and export values. While trade costs come in many forms, I assume in the present framework that they are summarized by a standard iceberg form in which a share, $\tau_s > 1$, of the good must be shipped in order for a whole unit to reach the destination. Under such a regime, export prices are a markup over domestic prices given by:

$$p_{sx}^n(\varphi) = \tau_s p_{sd}^n(\varphi) = \frac{\tau_s w^{1-\beta_s} i^{\beta_s} \nu_s}{(1-\theta_s)(1-\alpha_s)\varphi \cdot \rho}, \qquad \text{for } n \in \{H, F\} \tag{2.23}$$

Under costly trade, price indices vary across countries due to differences in the mass of firms, factor price differences, different variety prices charged in home versus export markets (due to variable trade costs), and differences in the number of exporters versus domestic-only producers (due to fixed and variable trade costs). An exporting firm in the home country receives the following revenue and profits from exporting:

$$\begin{aligned} r_{sx}^H(\varphi) &= \tau_s^{1-\sigma} \left(\frac{P_s^F}{P_s^H}\right)^{\sigma-1} \left(\frac{R^F}{R^H}\right) r_{sd}(\varphi) \\ \pi_{sx}^H(\varphi) &= \frac{r_{sx}^H(\varphi)}{\sigma} - f_{sx} \frac{(w^H)^{1-\beta_s}(i^H)^{\beta_s}\nu_s}{(1-\theta_s^H)(1-\alpha_s)} \end{aligned} \tag{2.24}$$

Since market entry costs are sunk, any firm with a productivity high enough to allow them to profitably export will also serve the domestic market, thus an exporting firm earns revenues and profits from domestic sales (given in (2.10)) plus revenue and profit from exporting.

As can be seen in the export profit equation, exporters must pay an additional fixed exporting cost,[24] f_{sx}, which results in an additional productivity cut-off for entry into the export market following from the zero-export-profit condition:

$$r_{sx}(\varphi_{sx}^*) = \sigma f_{sx} \frac{(w^H)^{1-\beta_s}(i^H)^{\beta_s}\nu_s}{(1-\theta_s^H)(1-\alpha_s)} \tag{2.25}$$

The export cut-off can then be related to the domestic cut-off in (2.11) by:

$$\varphi_{sx}^{*H} = \tau_s \left(\frac{P_s^F}{P_s^H}\right) \left(\frac{R^F}{R^H}\frac{f_{sx}}{f_s}\right)^{1/(\sigma-1)} \varphi_s^{*H} \tag{2.26}$$

[24] This can be thought of as capturing the costs involved with developing distribution networks in a foreign country, researching and complying with foreign regulations, etc.

The introduction of fixed and variable trade costs results in market segmentation, according to productivity. Firms that draw a productivity above the entry cut-off enter and serve the domestic market as under autarky. Of those, a share will draw a productivity level high enough to allow them to also enter the export market. This share is given by:

$$\chi_s^H = \frac{\left[1 - G(\varphi_{sx}^{*H})\right]}{\left[1 - G(\varphi_s^{*H})\right]} \tag{2.27}$$

2.5.1 Free Entry

As in the autarky or free trade cases, firms will choose to enter the market if they expect to earn revenues sufficient to cover the costs of entry. With the potential to earn profits in the foreign market as well as the domestic this free-entry condition is written as

$$V_s = \frac{\left[1 - G(\varphi_s^*)\right]}{\delta}\left[\bar{\pi}_{sd}^H + \chi_s^H \bar{\pi}_{sx}^H\right] = f_{es}\frac{(w^H)^{1-\beta_s}(i^H)^{\beta_s}\nu_s}{(1-\theta_s^H)(1-\alpha_s)} \tag{2.28}$$

where the average profit earned in each market is equal to the profits earned by a firm with average productivity in each segment: $\bar{\pi}_{sd}^H = \pi_{sd}(\tilde{\varphi}_{sd})$ and $\bar{\pi}_{sx}^H = \pi_{sx}(\tilde{\varphi}_{sx})$.

Similarly to the autarky or free trade cases, the free-entry condition can be written as a function of parameters and productivity cut-offs as

$$V_s = \frac{f_s}{\delta}\int_{\varphi_s^*}^{\infty}\left[\left(\frac{\varphi}{\varphi_s^*}\right)^{(\sigma-1)} - 1\right]g(\varphi)\mathrm{d}\varphi + \frac{f_{sx}}{\delta}\int_{\varphi_{sx}^*}^{\infty}\left[\left(\frac{\varphi}{\varphi_{sx}^*}\right)^{(\sigma-1)} - 1\right]g(\varphi)\mathrm{d}\varphi = f_{es} \tag{2.29}$$

where the export-productivity cut-off is linked to the entry cut-off as shown in (2.26). The expected value of entry is determined by the expected value of entering and serving the domestic market, plus a positive term capturing the expected value of entering and serving the foreign market. As in autarky, the value of entry is monotonically decreasing in φ_s^*.

2.5.2 Goods and Factor Markets

As in autarky, the mass of failing incumbent firms that exit is replaced by new entering firms drawing a productivity high enough to allow them to cover their production costs.

Under costly trade the sector price index is now influenced by the share of foreign producers that are productive enough to export as well as domestic producers, and is given by

$$P_s^H = \left[M_s^H\left(p_{sd}^H(\tilde{\varphi}_s^H)\right)^{(1-\sigma)} + \chi_s^F M_s^F\left(\tau_s p_{sd}^F \tilde{\varphi}_s^F)\right)^{(1-\sigma)}\right]^{1/(1-\sigma)} \tag{2.30}$$

Price indices now vary across countries due to differences in the mass of operating and exporting firms, and differences in factor prices and trade costs. The various influences affecting the domestic price index has important implications for understanding the effect that changes in trade policy can have on emissions demand that are absent from a representative-firm framework.

Finally, equilibrium sector revenues must account for expenditures by both domestic and foreign consumers:

$$R_s^H = M_s^H \eta_s R^H \left(\frac{p_{sd}^H(\tilde{\varphi}_{sd}^H)}{P_s^H} \right)^{1-\sigma} + \chi_s^H M_s^H \eta_s R^F \left(\frac{\tau_s \cdot p_{sd}^H(\tilde{\varphi}_{sx}^H)}{P_s^F} \right)^{1-\sigma} \tag{2.31}$$

where the first term captures revenues earned in sector s from domestic sales, and the second are revenues earned by the share of operating firms productive enough to also export. This equilibrium condition implies that all goods markets, world wide, will clear.

2.5.3 Costly Trade Equilibrium

The costly trade equilibrium is referenced by a set of 14 variables for home and foreign: $\{\varphi_s^{*n}, \varphi_{sx}^{*n}, P_s^n, p_s^n(\varphi), p_{sx}^n(\varphi), w^n, i^n, t^n, R^n\}$ for $s \in \{1,2\}$ and $n \in \{H,F\}$. These variables are determined by the combination of the free entry condition (2.29), the pricing rule (2.23), the productivity cut-off relationship (2.26), costly trade price indices (2.30), factor market clearing conditions (2.16), and the goods market clearing condition (2.31).

Proposition 3. *There exists a unique costly trade equilibrium, referenced by the vector* $\{\varphi_s^{*n}, \varphi_{sx}^{*n}, P_s^n, p_s^n(\varphi), p_{sx}^n(\varphi), w^n, i^n, t^n, R^n\}$ *for* $s \in \{1,2\}$ *and* $n \in \{H,F\}$.

Proof: See Appendix.

2.6 The Environmental Role of Firm Heterogeneity

Under costly trade, sector emissions are still given by (2.20), recognizing, however, that the aggregate output and price levels are now influenced by foreign as well as domestic variables. To evaluate the environmental role of firm heterogeneity in the combined framework, I first consider the effect of lowering trade barriers, from autarky to costly trade, when the relative prices of the two trading partners are identical. In this scenario, firms face a fixed cost of exporting but neither partner holds a comparative advantage in a given sector. Even so, the reduction in trade barriers still presents opportunities for gains from trade since consumers in each country value variety and firms differ in their response to the falling trade costs. In this

case, the environmental effect of falling trade costs works completely through within-sector reallocation across firms.

Proposition 4. *When relative prices are unchanged following a marginal reduction in trade barriers, trade induced endogenous productivity gains will result in higher aggregate output, lower aggregate emissions intensity, but total factor demands in either sector will be unaffected and the aggregate emissions level will remain unchanged.*

Proof: See Appendix

The intuition for this result can be understood in two ways. First, due to the assumption that productivity is neutral in production, as is common in the heterogeneous-firm trade literature, any given firm's choice of emissions relative to their capital and labor inputs is independent of their productivity level.[25] This is true at the sector level as well after aggregating across heterogeneous firms. Thus, changes in the economic regime that do not affect relative prices or movement of capital and labor between sectors will leave total emissions unchanged. The second way to understand this is to again decompose the emissions given in (2.20) into aggregate output and aggregate emissions intensity:[26] $Z_1 = \frac{R_1}{P_1} \cdot \frac{\alpha_1 P_1}{t_1}$, where, in contrast with the free-trade scenario, the sector price index is given by (2.30). As in *Proposition 2*, total sector revenue will adjust according to a country's comparative advantage, driven by changes in factor allocations and relative factor price adjustments that adjust as relative output prices adjust as trade costs fall.

When the relative output prices between trading partners are the same–as is case when fixed costs across sectors, and relative endowments and size across countries are the same–relative wages and thus sector factor allocations are unchanged following a trade liberalization. Thus total sector revenue in each sector does not adjust. In the presence of costly trade, and heterogeneous firms, however, the price index in each sector does adjust, even in the absence of relative wage adjustments. In particular, the value of entry under costly trade is given by (2.29) which rises as trade costs decline, and thus falling trade costs induce a rise in the productivity cut-off which in turn raises average productivity in all sectors, both at home and for the trading partner. Individual firms will still seek to serve the foreign market and will accordingly bid up the real return for additional inputs. Due to the presence of a fixed cost of trade, firms must be able to earn higher profits to cover the rising factor costs. Less productive firms will have lower revenues and profits and will thus shed resources, in the extreme, shedding all of their resources and exiting the market.

Competitive reallocation within each sector thus shifts capital and labor resources towards more productive firms, and sector price indices fall. Real output rises–driving

[25] As can be seen in (2.8)

[26] Noting that $R_s = Q_s \cdot P_s$

up emissions demand–and emissions intensity falls–reducing emissions demand. In the absence of cross-sector resource movement, and when productivity is Hicks-neutral, these two outcomes exactly off-set, and total emissions will remain unchanged. Of course, much of global trade goes on between countries that do in fact differ in their comparative advantage. I move now to analyze the combined environmental effect of a trade liberalization under costly trade when the trading partners relative prices differ, and thus both within and across sector channels are operating.

2.7 The Combined Effect

When countries differ in their comparative advantage, and when fixed costs are a key barrier influencing firm's decision regarding whether or not to export, the environmental responses to trade liberalization within and across sectors will interact. As in much of the related literature, using the fact that $R_s = Q_s \cdot P_s$, emissions demand from (2.20) can be decomposed into scale, composition, and technique effects:

$$Z_1 = \underbrace{Q}_{\text{Scale}} \times \underbrace{\frac{1}{1+Q_2/Q_1}}_{\text{Composition}} \times \underbrace{\frac{\alpha_1 P_1}{t_1}}_{\text{Technique}} \tag{2.32}$$

where total output, the scale effect, is given by $Q = Q_1 + Q_2$, and the costly-trade price index is given by (2.30).

In contrast to a representative firm framework, these three effects are now also influenced by fixed costs and heterogeneous firms which affect the productivity cutoff and thus average productivity and the mass of firms. In contrast to a single sector framework, total inputs in a sector are not fixed, but can adjust according to the country's comparative advantage. Using (2.12) and the pricing rule from (2.30), the composition and technique effects can be re-written as

$$\text{Composition} : \left(\frac{M_1}{M_2}\right)^{1/\rho} \frac{q_1(\tilde{\varphi}_1)}{q_2(\tilde{\varphi}_2)} \quad , \quad \text{Technique} : \frac{(1-\theta_1)^{(1-\alpha_1)/\alpha_1}}{M_1^{1/(\sigma-1)}\tilde{\varphi}_1\rho} \cdot \psi_1 \tag{2.33}$$

where ψ_s,[27] captures a "trade" or "competitiveness" component of the technique effect working through the sector price indices.

[27] $\psi_s \equiv \left[1 + \frac{\chi_s^F M_s^F \tau_s^{1-\sigma} \cdot \left(p_s^F(\tilde{\varphi}_{sx}^F)\right)^{1-\sigma}}{M_s^H (p_s^H(\tilde{\varphi}_s^H))^{1-\sigma}}\right]^{1/(1-\sigma)}$

Increases in total output, the scale effect, raise emissions demand holding the sector-share of output and the sector emissions intensity constant. This is the increase that would result if production inputs in the economy were simply scaled up in equal proportion and there was no cross-sector shift of resources or any change in production techniques. The composition effect raises emissions if the share of output produced by the polluting sector increases, due to a relative increase in average output or the mass of operating firms. The technique effect captures change in emissions due to changes in emissions intensity of the sector. Decomposing the total effect into scale, composition, and technique effects reveals that each of the three effects is augmented by the influence of heterogeneous firms and within-sector reallocation in ways that have implications for future theoretical as well as empirical research. In particular, scale, composition and technique effects due to comparative advantage, specialization, and environmental policy, now interact with individual firm's decisions within each sector that affect the productivity cut-off:

Proposition 5. *The opening of costly trade in the presence of heterogeneous firms augments each of the traditional scale, composition, and technique effects driving emissions demand:*

(a) The increase in average sector productivity raises output and emissions demand via a scale effect, thus magnifying the influence of specialization.

(b) The increase in productivity raises average output, $\bar{q}_s$, in all sectors. Other things equal, the largest increase occurs in the comparative advantaged sector and emissions demand rises via the composition effect if the emissions intense sector holds the comparative advantage.

(c) The increase in productivity lowers the relative mass of firms putting downward pressure on emissions demand. This dampens, but does not reverse, the rise in emissions demand due to the composition effect.

(d) The increase in productivity lowers emissions intensity and emissions demand via the technique effect, even when the relative cost imposed by environmental policy is fixed.

Proof: See Appendix.

This proposition highlights several results, summarized by the point that correctly evaluating changes in emissions due to the scale, composition, and technique effects requires consideration of factors influencing cross-sector comparative advantage as well as heterogeneous firm response within-sectors. In a neoclassical model, the scale effect is driven by specialization and corresponding output gains due to trade. In the combined framework, when trade involves additional fixed investment costs, endogenous productivity gains serve to further raise output, and thus presents an additional channel driving up emissions demand via the scale effect.

In addition to the shift of resources across sectors driven by comparative advantage, discussed in *Proposition 2*, the presence of fixed costs and heterogeneous firms induces two new channels working through the composition effect via changes in relative average output and the relative mass of firms. Following a reduction in trade barriers, the productivity cut-off rises as does average productivity in all sectors. Exporting is more attractive in the comparative advantage sector, due to difference in relative prices, and thus the free-entry productivity cut-off rises by more in the comparative advantage sector.

Average sector output is an average of domestic and export production and is given by:

$$\bar{q}_s^n = \left(\frac{\tilde{\varphi}_s^n}{\varphi_s^{n*}}\right)^{\sigma} \varphi_s^{n*} f_s(\sigma - 1) + \chi_s^n \left(\frac{\tilde{\varphi}_{sx}^n}{\varphi_{sx}^{n*}}\right)^{\sigma} \varphi_{sx}^{n*} f_{sx}(\sigma - 1) \tag{2.34}$$

Following a reduction in trade barriers, the greater rise in the productivity cut-off in the comparative advantaged sector raises average output by more than in the other sector, and relative average output rises, thus raising emissions demand.

The mass of firms in a sector is given by $M_s^n = R_s^n/\bar{r}_s^n$. Due to the presence of trade costs, only a subset of operating firms will find it profitable to export. As trade barriers fall, the value of exporting rises and more productive firms increase their demand of inputs in order to serve the newly accessible foreign market. This raises factor prices and drives less productive firms from the market, raising the free-entry cut-off, φ_s^*, and lowering M_s^n. However, as shown in *Proposition 2*, the total effect of a trade liberalization is to change the relative mass of firms according to the country's comparative advantage: M_1^n/M_2^n rises at home, but falls in the foreign country. Relative movement of resources across sectors dominates the influence of changing productivity captured in the composition effect. Relative to the neoclassical framework, the traditional composition effect is dampened but will not be reversed by endogenous productivity gains due to the inclusion of fixed costs and heterogeneous firms.[28]

When a country holds a comparative advantage in dirty production, the composition effect raises emissions demand. However, the effect is moderated by the heterogeneous response of firms. In particular, falling trade costs drive firms to attempt to serve the export market and consequently bid up input prices.[29] This competitive effect drives out the least productive firms (who are the most emissions intense) and thus moderates the composition effect. On the other hand, if the country holds a comparative advantage in clean production, the composition effect will reduce emissions demand, but this effect will also be moderated. In this case, falling relative prices means that relative prices of inputs used in the polluting sector are also falling, and thus some less efficient firms will be able to remain in the market

[28] A similar result regarding employment is highlighted by Bernard et al. (2007b).

[29] This is true in both the comparative advantage sector as well as the comparative disadvantaged sector.

who would otherwise have been forced out as other firms bid up factor returns to increase their exports.

Finally, endogenous productivity gains influence production techniques. In the homogeneous firm framework per-unit emissions are only reduced following a trade liberalization if paired with an increase in the relative stringency of environmental regulation that induces firms to increase the share of resources devoted to abatement. In the combined framework, even if this channel is held fixed and environmental policy leaves emissions intensity unchanged at the firm level, the productivity gains induced by rising factor costs following a trade liberalization result in the least productive and most emissions intense producers exiting the market and thus represent an additional endogenous channel reducing emissions intensity in a given sector.

Analysis of the combined framework under costly trade provides two key insights. First, while the presence of fixed costs and heterogeneous firms represents an important channel affecting a country's emissions, when total emissions are the concern, a country's comparative advantage–stemming from differences in relative endowments or environmental policy (or fixed costs)–will ultimately determine whether trade liberalization raises or lowers emissions. Thus, lowering trade barriers in a country holding a comparative advantage in capital and emissions intense production will raise emissions demand and pollution will rise unless environmental policy increases sufficiently in stringency. However, the combined framework highlights the second point that when fixed trade costs are a key factor influencing firms' export and production decisions, the heterogeneous response by firms following a trade liberalization interact with systematic cross-sector effects and are an important channels influencing sector output and production techniques. These results contribute a plausible explanation of why previous studies examining the environmental effect of trade without accounting for fixed trade costs and resulting heterogeneous selection response by firms, have found relatively small composition effects but relatively large scale and technique effects.[30] Empirical work evaluating the environmental effects of trade must take these interaction effects seriously.

Finally, the combined framework offers an important implication for the environmental policy response to trade. While the combined framework maintains the insight highlighted by Antweiler et al. (2001) that environmental policy will be required to reverse a rise in emissions if a country holds a comparative advantage in relatively dirty production, *Proposition 5* emphasizes the point that design of an efficient policy will require consideration of the fact that endogenous productivity gains will drive down a sector's emissions intensity and will moderate the composition effect. A policy that fails to account for the presence of fixed costs

[30]See for example Levinson (2009); Antweiler et al. (2001)

and heterogeneous selection by firms, may raise environmental stringency by more than is necessary to satisfy their policy objective, and thereby unnecessarily reduce the country's comparative advantage and reduce welfare. Accounting for the role of fixed costs and the underlying selection of firms following a trade liberalization, will be key to designing effective environmental policy.

2.8 Conclusion

This is the first paper combining a heterogeneous-firm framework with cross-sector comparative advantage to examine the environmental effects of trade. The primary message of the resulting combined framework is at once both simple and complex. Simple in that it highlights the message that, when fixed costs are an important determinant of firm's export and production decisions, both comparative advantage influencing cross-sector responses to trade liberalization, and heterogeneous firm responses within sectors are interacting to affect our environment. This conclusion is substantiated by an empirical exercise using emissions data from US manufacturing facilities that emphasizes for future empirical research that omitting consideration of either of these two channels will result in missing a substantial influence on environmental outcomes. The combined framework further shows that the presence of heterogeneous firms and fixed costs leads to endogenous productivity gains that magnify the traditional scale effect, reduce emissions intensity via the technique effect, and moderate the composition effect, relative to a representative firm framework.

The paper's message is complex in that it suggests that future research concerning the effect of trade on our environment must carefully account for the interaction of factors driving within-sector firm-selection, and endogenous productivity gains with factors influencing cross-sector resources shifts when evaluating the effect of trade cost or environmental policy changes on environmental outcomes.

Finally, for environmental policy makers the combined framework presents two cautions. First, when firms face substantial fixed costs of entry and production, rising environmental stringency can affect firms' intensive decision regarding how much to produce and what technology to employ, as well as their extensive decision regarding whether to continue producing or to exit altogether. Recognizing and accounting for this potential is key for the efficient design of policy. Second, for consumers and policy makers alike, the model emphasizes the means by which competition works to endogenously reduce emissions intensity. However, these emissions intensity reductions will not correspond to reductions in total environmental performance when firms' productivity is neutral, and emissions intensity reductions should not be interpreted necessarily as leading to reductions in total emissions.

Chapter 3

Environmental Policy in the Presence of Heterogeneous Firms

This paper is collaborative work with J. Scott Holladay at the University of Tennessee

3.1 Introduction

Emissions from U.S. manufacturing have fallen dramatically over the past 30 years, while real manufacturing output has steadily risen.[1] The specific drivers underlying this reduction have remained a puzzle. The economics literature has suggested that increasing environmental regulation, changing composition of the manufacturing industry, and reduced emission intensity of production, are all possible causes. At the same time, the impact of environmental regulation on polluters and workers in polluting industries has been a focus of policy makers, the media and the economics literature. Much of the attention in this literature has focused on the questions of how industry-wide environmental regulations affect firms' production and abatement decisions, as well as their location and entry or exit decisions, and how these firm-level decisions affect emissions outcomes.

This paper addresses the question of how changes in environmental policy affect aggregate emissions intensity when operating within and across firms. To answer this question, we first develop a general equilibrium model in which heterogeneous firms may emit pollution, can adjust their emissions intensity through investments in abatement, and are free to enter and exit monopolistically competitive markets. These polluting firms use capital and labor to produce output and pollution emissions, which we model as a joint input in production. Polluters face environmental regulation and can choose to invest resources in an available marginal abatement technology to reduce their emissions intensity. To produce, firms must first pay a fixed cost of entry and randomly draw a productivity. Those firms with a productivity draw sufficiently high to allow them to profitably cover their fixed costs of production will enter the market and maximize profits subject to factor costs and environmental regulation. This free-entry condition generates a link between firm productivity and aggregate emissions intensity (AEI), as the most productive firms will operate at the lowest emissions intensity levels, which is consistent with existing literature.

The key advantage of the general equilibrium framework we develop is that it allows us to decompose the effect of environmental regulation on pollution emissions (and polluting firms) into two channels. The first is the direct effect of existing firms generating less emissions in production as they respond to the increased price of emitting by increasing abatement. We term this channel the intensive margin. The second is the increase in exit from the regulated industry, which reduces output and thus emissions. These channels have very different impacts on polluting industries. Response at the intensive margin leads to reduced pollution

[1] EPA (US Environmental Protection Agency Air Quality Report, 2012)

emissions without reducing the size of the industry while reduced pollution emissions at the extensive margin are associated with the industry shrinking and the attendant concerns regarding employment, market power, and pollution havens.

We first describe the model and the channels through which environmental policy and fixed costs interact to affect aggregate emissions and AEI. We then evaluate the model empirically using an industry-year panel of approximately 400 U.S. manufacturing industries from 1990-2007. We match emissions data from the EPA's Toxic Release Inventory with industry data in the NBER-CES database. We then create several measures of fixed costs and devise two unique measures of environmental stringency which we use to estimate a series of empirical models and find evidence consistent with the predictions of the model.

The model and empirical results allow us to make several distinct contributions to the literature. First we analyze how polluting industries respond to environmental regulation. Our theoretical framework allows us to separate the impacts of environmental regulation on the emissions intensity of existing polluters from the impact of environmental regulation on polluting firms' entry and exit decision. Recent work, for example Levinson (2009) and Shapiro and Walker (2015), has identified the influence of environmental regulation on within industry emissions intensity as one of the most important sources of the recent fall in manufacturing pollution intensities. Our approach allows us to extend that literature by decomposing that change into an intensive and extensive margin.

A second, closely related, contribution is to use the model and empirical results to determine which industries are most adversely affected by increases in environmental regulation. The extent to which the polluting industries respond to environmental regulation at the intensive margin has been the matter of much debate in the literature. Greenstone (2002) and List et al. (2003) explore the impact of a particular suite of environmental regulations, based on the Clean Air Act's non-attainment designation, on the location decision of polluters as well as employment and output in polluting industries. They find small, but significant, impacts of environmental regulation. We focus on the the interaction between fixed costs and environmental policy since our theory suggests that fixed costs are important factors affecting the impact of of environmental policy on aggregate environmental outcomes by affecting firms' responses at the extensive margin.

We make an additional methodological contribution in defining new measures of environmental regulation, and fixed costs of production and examining their quality using various theoretical predictions from our framework and related literature. Measuring the level of environmental regulation facing polluting firms is difficult.[2] The preferred measure of environmental stringency that we develop exploits exogenous variation in regulation

[2]See Brunel and Levinson (2016) for an overview of the literature on measuring environmental regulation.

arising from the Clean Air Act non-attainment status, similar in spirit to the measures of environmental regulation employed in Henderson (1996) and Greenstone (2002). The regulation is enacted at the federal level with variation in the ambient concentration of pollution level driven largely by weather patterns resulting in geographic and temporal variation in environmental stringency.

Our model suggests that industry fixed costs are a particularly important factor magnifying the effect of environmental regulation on polluting industries. In particular, when individual firms differ in their productivity, higher fixed costs raise total production costs–which drives polluting firms out of the market. Ryan (2012) shows that increases in environmental regulation have led to significant increases in fixed costs and increased market power in regulated industries. To proxy for fixed costs of entry, we consider multiple measures suggested by related literature and examine their quality and plausibility by regressing them on several important aggregate margins suggested by related heterogeneous-firm literature, including market size, market concentration, and aggregate productivity. Our preferred measure, based on this analysis and following Helpman et al. (2004), is the share of non-production workers per firm in each industry. While Ryan (2012) explores the environmental effect of the Clean Air Act amendments, modeled as increases in fixed costs for regulated firms, we focus on the interaction between fixed costs and environmental policy as two separate mechanisms. Consistent with the theoretical framework, we find that higher fixed costs tend to magnify the negative effects of environmental stringency on AEI, working through changes both in firms' extensive and intensive margin decisions.

This paper contributes to a large literature, including Keller and Levinson (2002); Greenstone (2004); Cole et al. (2005), and Shadbegian and Gray (2005) evaluating the rapid decline in pollution emissions from U.S. manufacturing. This literature generally focuses on the overall reduction in emissions from manufacturing without analyzing separate channels through which environmental regulation affects firms' intensive and extensive decisions, or evaluating the channels through which endogenous market competition can affect industry level emissions intensity. Heutel (2011) develops a dynamic model of firms' abatement decisions, but the model and following empirical work investigate the role of environmental regulation on within-firm adjustment, and does not consider the effects of policy on entry and exit.

Our efforts to quantify environmental regulation contribute to a literature that recognizes the difficulty of assessing the stringency, and form, of regulation that polluters face, for example Henderson (1996). Because costs associated with environmental performance can take numerous forms including environmental fines or taxes, permitting costs and compliance fees, emissions targets that require installation of costly abatement technology, or input

substitution requirements, Levinson (2008, p. 1) notes that "[t]he problem is not merely one of collecting the appropriate data; merely conceiving of data that would represent [environmental stringency] is difficult." What is particularly relevant in our estimation is that environmental regulation can manifest as a marginal or variable cost or as a fixed production cost or as a sunk cost. While our theory is agnostic about the source of the fixed costs that firms face, and treats environmental regulation as a unit tax, we show, theoretically, that the form of the costs that firms face generates distinctly different responses across firms that influence AEI outcomes. Our approach interacts various measures of environmental stringency with measures of fixed costs to evaluate the channels affecting emissions outcomes within and across sectors.

This paper shows that accounting for cross-sector differences in environmental policy, and fixed costs, and the way that they interact to affect entry and exit within sectors, is key to understanding the means by which environmental policy changes and market characteristics affect our environment. These effects and interactions are of particular importance for those concerned with the efficient design of environmental policy.

The remainder of the paper is structured as follows. Section 2 describes the basic model and mechanisms through which environmental policy and fixed costs affect emissions outcomes. Section 3 describes the data sets and construction of key variables used in estimation. Section 4 lays out the empirical specification and estimation strategy and describes the results. Section 5 presents several robustness exercises and Section 6 concludes.

3.2 Theory

We introduce heterogeneous, polluting firms, differing in their productivity levels, into a simple multisector model, in which firms face fixed production costs and environmental regulation. Our model highlights the important role of environmental policy to affect environmental outcomes through both an intensive effect on firms' production and abatement decisions, and an extensive margin effect on firms' entry and exit decisions. The model further shows that the magnitude of the environmental policy effects differs systematically across sectors with differences in fixed costs, which are key factors determining the degree of entry and exit, and average productivity in the sector as well as other aggregate outcomes.

3.2.1 Model

Following LaPlue (2016b), we consider a setting where consumers have CES preferences over different product varieties within a sector and Cobb-Douglas preferences across sectors. The

country is home to a continuum of firms, each producing a differentiated variety using capital (k) and labor (l) with a constant returns to scale production technology. Firms may generate pollution, $z = e \cdot q$, where q is the firm's output and e is their per-unit emissions. Polluting firms may choose to divert a share of their resources, $\theta \in (0, 1)$, to an abatement activity which lowers their emissions intensity. In addition, firms in any sector, s, have a unique productivity level, φ,[3] and their production process, net of resources devoted to abatement, takes the following form:

$$q_s(\varphi) = (1 - \theta_s)\varphi k^{\beta_s} l^{1-\beta_s} \tag{3.1}$$

where the β_s parameter captures the share of their costs that firms divert to covering capital costs.

We follow LaPlue (2016b) in assuming that firms' emissions per unit of net-output take the following form:[4]

$$e_s(\varphi) = \frac{(1 - \theta_s)^{\frac{1-\alpha_s}{\alpha_s}}}{\varphi} \tag{3.2}$$

where $0 < \alpha_s < 1$ is a technology parameter governing the efficiency of available abatement activities. A smaller α_s implies a more efficient technology, and any given abatement activity will result in lower emissions intensity and relatively fewer emissions. Firms that undertake more abatement will have lower per-unit emissions, as will more productive firms. Polluting firms thus choose how much capital and labor to hire to achieve a level of output, and how much emissions to release, given an abatement-share decision. Using equations (3.1) and (3.2), a firm's net-production function can be written as a function of these three choices:

$$q(\varphi) = \varphi(k^{\beta_s} l^{1-\beta_s})^{1-\alpha_s} z^{\alpha_s} \tag{3.3}$$

As in related heterogeneous firm models (e.g. Hopenhayn (1992); Melitz (2003)), firm production costs entail a variable as well as fixed component, denoted f_s. We assume that fixed and variable production require the same factor content, and thus a firm's cost function is given by:

$$\Gamma_s(\varphi) = \left[\frac{q(\varphi)}{\varphi} + f_s\right] \cdot (w^{1-\beta_s} i^{\beta_s} \nu_s)^{1-\alpha_s} \tau_s^{\alpha_s} \zeta_s \tag{3.4}$$

where w, i, and τ_s represent wages, rental rate, and an effective emissions tax imposed by environmental policy.[5] We term this an "effective tax," and will use it interchangeably

[3] Consequently, φ indexes individual firms and varieties.

[4] This captures the idea that abatement is costly, without adding undue complexity to the general equilibrium model.

[5] The variables $\zeta_s = (1-\alpha_s)^{\alpha_s - 1}\alpha_s^{-\alpha_s}$ and $\nu_s = (1-\beta_s)^{\beta_s - 1}\beta_s^{-\beta_s}$ are positive functions of abatement and production technology parameters.

with "environmental stringency," because the means by which emissions are regulated and controlled can take many forms including pollution taxes, cap-and-trade systems, and technology standards. However, in equilibrium the costs imposed by these various forms of regulation can be written equivalently as a per-unit tax.[6] Factor input prices and technology parameters are taken by firms as given. LaPlue (2016b) shows how the combination of CES consumer preferences and this cost structure leads to a firm-level emissions demand function that is decreasing in environmental stringency,[7] and increasing in the firm's productivity level, as more productive firms are able to lower their prices and attract more demand. However, because our model allows for potential entry and exit, influenced by the firm's specific productivity level and the presence of several variable and fixed costs, we must carefully aggregate the firm-level values in order to evaluate the effect of policy changes on aggregate emissions.

3.2.2 Free Entry

Aggregate price, output, and emissions outcomes are a function of firms' intensive choices regarding what inputs to hire and what level of abatement activity to undertake, as well as an extensive decision regarding whether to enter, remain in, or exit the market. These equilibrium decisions are determined by the combination of a zero-profit condition and a free-entry condition.

First, due to the CES preference structure, a firm's optimal price will be a constant markup over their marginal costs. Consequently, more productive firms are able to lower their prices and increase revenues and profits. If an entering firm draws a productivity level too low to allow it to profitably cover the fixed costs of production, f_s, the firm will exit. This zero-profit condition establishes a minimum cut-off level of productivity which we denote φ_s^*.

Second, in order to enter a market, a firm must pay a sunk entry cost, f_{es}, which we assume requires the same factor inputs as fixed production costs.[8] In equilibrium, firms will choose to enter a market as long as the expected value of entry is sufficient to cover the entry cost.[9]

The combination of these two equilibrium conditions–zero-profit cut-off (ZPC) and free-entry (FE)–create a two equation system linking profits to productivity and are sufficient to establish a unique equilibrium productivity cut-off as a function of expected profits. A

[6] Copeland and Taylor (2003) discuss, at great length, the efficiency concerns associated with different forms of regulation.

[7] A firm's optimal choice of abatement share, θ_s , is determined by cost minimization. See appendix.

[8] This is a common, though strong, simplifying assumption in heterogeneous firm models (e.g. Melitz (2003); Bernard et al. (2007b))

[9] See appendix for mathematical treatment and discussion.

graphical representation of this relationship, taken from Melitz (2003), is presented in Figure (E.1).

A couple of things are worth noting with regard to this figure. First, a rise in fixed production costs shifts the zero-profit curve out. This rise in production costs lowers firms' profits and raises the minimum productivity level required to successfully remain in the market, thus serving to reduce both the number of firms operating in the market as well as total output. However, because of the resulting rise in the productivity cut-off, the remaining firms will, on average, be larger and more productive. Failing to recognize the general equilibrium selection effects of this rise in fixed costs could give rise to the faulty conclusion that raising fixed costs raises productivity and thus raises output and welfare.[10]

Second, consider the effect of a change in environmental stringency. An increase in environmental stringency will raise production costs for firms, and causes the zero-profit curve to shift out. However, the change in environmental stringency also raises entry costs, thus raising a barrier to entry that serves to protect incumbent firms, captured by an inward shift of the free-entry curve. Under the standard assumption, in heterogeneous firm models with free entry, that fixed costs of production and entry use the same factor intensity, these two shifts exactly off-set one-another and there is no change to the productivity cut-off, φ_s^*, or average productivity, although average profits in the sector unambiguously decline. If this assumption is relaxed, for example so that entry does not generate emissions that entail environmental payments, then a change in environmental stringency would serve to raise the relative costs of production, relative to the cost of entry, and induce an additional increase in the productivity cut-off. The following analysis follows existing literature by maintaining the assumption that entry and production utilize the same factor intensities.

3.2.3 Aggregate Emissions Intensity

Using these equilibrium free-entry and zero-profit cut-off conditions, previous work by LaPlue (2016b) shows how firms' emissions demand can be aggregated and written as a concise function of the available abatement technology parameter, α_s, sector revenue, R_s, and environmental stringency:[11]

$$Z_s = \frac{\alpha_s R_s}{\tau_s} \tag{3.5}$$

[10] This observation is in contrast to the much debated "Porter Hypothesis" that suggests the possibility that productivity gains could in part or in full offset higher costs coming in the form of more stringent environmental regulation, see Porter and Linde (1995).

[11] Throughout, capital letters will denote aggregate variables, while lowercase letters will denote firm-level variables.

In equilibrium, more stringent environmental policy reduces emissions demands, an improvement in available abatement technologies lowers emissions demand, as captured by a smaller α_s, and positive aggregate revenue shocks raise emissions demand, *ceteris paribus*. Though true to the underlying firm-level setup, this aggregate equation conceals several important channels influencing emissions demand, including the role of endogenous firm entry and additional effects of environmental policy that also influence sector revenue. Recognizing that $R_s = Q_s \cdot P_s$, where Q_s is sector-specific aggregate output, and P_s is a sector price index, we decompose emissions demand and focus on aggregate emissions intensity, $E \equiv \frac{Z_s}{Q_s} = \frac{\alpha_s P_s}{\tau_s}$, which in turn can be decomposed into the mass of firms, M_s,[12] and the average emissions intensity or emissions intensity of the average firm, $e(\tilde{\varphi}_s)$. Thus, changes to aggregate emissions intensity, E, can be thought of as operating through either across-firm reallocation, within-firm technique adjustment, due to abatement, or both:

$$AEI_s = \underbrace{M_s}_{\text{Across Firm Reallocation}} \times \underbrace{e(\tilde{\varphi}_s)}_{\text{Within Firm Techniques}} \tag{3.6}$$

where, as in Melitz (2003), $\tilde{\varphi}_s$ represents weighted average productivity in the sector,[13] or productivity of the average firm, and is monotonically increasing with the corresponding sector productivity cut-off. Thus, if either the mass of firms or average emissions intensity in a sector increases, AEI will increase, *ceteris paribus*.

Using equilibrium conditions taken from LaPlue (2016b), these two endogenous channels can be further decomposed to see the underlying influences.[14] This decomposition clarifies the theoretical relationship between these endogenous channels and our variables of interest: environmental regulation (captured by the emissions tax variable) and fixed costs. The model presents entering firms as making a draw from a distribution, and we follow related literature[15] in assuming that productivity follows a Pareto distribution. In addition to being a reasonable match of existing data,[16] the Pareto distribution is tractable and allows for

[12] For expositional convenience the reader may refer to M_s as the number instead of mass of firms without loss of generality.

[13] The average productivity measure is weighted by sales share.

[14] The equilibrium conditions and the decomposition steps are detailed in the appendix.

[15] See Helpman et al. (2004); Bernard et al. (2007b)

[16] See Arkolakis et al. (2012); Axtell (2001)

straightforward closed-form solutions:

$$AEI_s = \underbrace{\frac{\lambda_s}{f_s \cdot \tau_s^{\alpha_s}}}_{\text{Across Firm}} \times \underbrace{\left(\frac{\Omega_s}{\lambda_s^{\frac{1}{\rho}}}\right) \cdot \frac{f_s^{\frac{1}{\rho}-\frac{1}{c}}}{\tau_s^{(1-\alpha_s)-\frac{\alpha_s}{\rho}}}}_{\text{Within Firm}} \tag{3.7}$$

where $\lambda_s = \frac{\eta_s R}{\left(\frac{c}{\gamma}\right)\sigma(w^{1-\beta_s} i^{\beta_s} \nu_s)^{1-\alpha_s} \zeta_s}$ and $\Omega_s = \frac{\left(w^{1-\beta_s} i^{\beta_s} \nu_s \frac{\alpha_s}{1-\alpha_s}\right)^{1-\alpha_s} \cdot f_{es} \cdot \delta}{\left(\frac{c}{\gamma}\right)^{\frac{1}{\sigma-1}} \rho\left[\left(\frac{c}{\gamma}-1\right)\kappa^c\right]^{\frac{1}{c}}}$ capture variables and parameters that are unaffected by changes in environmental policy or fixed costs.[17]

These channels can be further combined, using the fact that $\rho = \frac{\sigma}{\sigma-1}$, to see the full effect of a change in environmental policy or fixed costs:

$$AEI_s = \left(\frac{\Omega_s}{\lambda_s^{\frac{1}{\sigma-1}}}\right) \frac{f_s^{\frac{1}{\sigma-1}-\frac{1}{c}}}{\tau_s^{1-\frac{\alpha_s}{\rho}}} \tag{3.8}$$

We focus our analysis concerning AEI on the role of two policy-relevant variables: environmental stringency and fixed costs and discuss the theoretical implications of these two variables for emissions outcomes in the following predictions.

3.2.4 Hypotheses

In order to analyze the channels through which changes in environmental policy affect environmental outcomes, and how those affects are influenced by the presence of fixed production costs, we first analyze the combined effect and then consider how policy changes work through each of the two aggregate channels–the mass of firms cross-firm channel and the average emissions intensity within-firm channel.

Combined

Our primary concern is how environmental policy changes affect AEI, given in (3.8). To capture this effect requires only the assumption that $\sigma > 1$. This assumption is both common in related literature and supported by empirical evidence. For example Oberfield and Raval (2014) estimate that, on average, consumers' elasticity of demand is near 3.89 and for no sector does it drop below 2.9. We summarize the relationship between environmental

[17]The parameter η_s captures the share of income that consumers devote to a given sector, R is national income, which is pinned down by capital and labor endowments and equilibrium factor returns, similar to an approach followed by Copeland and Taylor (2003). Consumers' constant elasticity of substitution is captured by σ and $\rho \equiv \frac{\sigma-1}{\sigma}$. Finally, c, γ, and κ are all parameters of the Pareto distribution.

regulation and AEI in the following hypothesis:

Hypothesis 1: A rise in environmental stringency lowers aggregate emissions intensities.

We are also concerned with how the presence of fixed costs may influence the environmental affects of policy changes. To understand this affect we make use of the additional assumption that $c > \sigma - 1$, following Bernard et al. (2007b), which ensures that the variance of log productivity is finite. Increases in fixed costs–which generate higher costs and higher average productivity–will not generate exponential productivity gains strong enough to overcome the adverse affects of rising costs and resource diversion to fixed costs rather than output. Under this additional assumption, higher fixed costs raise AEI. We summarize the direct and interaction effects in the following hypothesis:

Hypothesis 2: A rise in fixed costs raises AEI and magnifies the effects of a change in environmental stringency.

In sectors that have relatively high fixed costs, the marginal reduction in AEI is of greater magnitude following a rise in environmental regulation, than in sectors with lower fixed costs. We explore the intuition underlying these results in the following sections as we explore the across firm and within firm channels introduced above.

Reallocation Across Firms

As discussed above, the effects of environmental policy and fixed costs influence AEI through two endogenous channels, the first being across-firm reallocation captured by changes in the mass of firms. Examining equation (3.7), a rise in environmental stringency unambiguously lowers the mass of firms thereby lowering AEI.

Hypothesis 3: A rise in environmental stringency lowers the mass of firms.

A rise in environmental stringency raises costs, generally, for polluting firms in the sector which raises the minimum revenue that firms must achieve to remain profitable in the market, resulting in the exit of polluting firms which drives down AEI. This direct of environmental policy is also affected by the presence of fixed costs, as summarized in the following hypothesis:

Hypothesis 4: An increase in fixed costs lowers the mass of firms, and moderates the effect of environmental policy.

The magnitude of the reduction in emissions intensity due to rising environmental stringency is reduced in sectors with relatively high fixed costs because these sectors already have a relatively small number of operating firms, since higher fixed costs tend to decrease the number of firms operating in a given sector. Thus, a rise in environmental stringency will cut out fewer firms in a sector that already has fewer firms. Note that if equation (3.7) is log-linearized, there would be no interaction between fixed costs and environmental stringency, though, of course, if the model were more complex even a log-linearization might not preclude the interaction. Related to this, the percentage change in AEI (in the current model) following a rise in fixed costs will be the same in the two sectors, but the magnitude of the effects will differ.

Within Firm Adjustment

We first analyze the effect of an increase in the emissions tax on the average emissions intensity, $e(\tilde{\varphi}_s)$, which is the within firm component of (3.7). Understanding this effect is complicated by the fact that a rise in environmental stringency induces two competing general equilibrium effects on average emissions intensities. The first is a substitution effect, captured by the $(1-\alpha_s)$ exponent on the tax for the within-firm component of equation (3.7). A rise in environmental stringency motivates firms to substitute away from emissions and towards other inputs, thereby lowering average emissions intensity.

The second effect arises since the same increase in environmental stringency will result in a general rise in costs in the sector which will reduce firms' output, thereby increasing average emissions intensity. This competing effect is captured by the negative $\frac{\alpha_s}{\rho}$ exponent on the tax in the within-firm component of equation (3.7). The substitution effect will dominate and the net results will be a reduction in average emissions intensity only if $(1-\alpha_s) > \frac{\alpha_s}{\rho}$. Though an abundance of evidence regarding the values of these parameters does not exit, the little bit of available evidence suggests that this is a plausible assumption. For example, work by Shapiro and Walker (2015) suggests that α may be near 0.011 on average, while estimates of σ by Oberfield and Raval (2014) suggest an average value for ρ near 0.74. These parameters assumptions amount to assuming that consumers' elasticity of substitution, σ, is substantially greater than one, while the cost-share that firms allocate to environmental expenses is substantially less than one. We summarize this conclusion in the following hypothesis:

Hypothesis 5: A rise in environmental stringency lowers average emissions intensities in polluting sectors.

Finally, we consider the effect of fixed costs on average emissions intensity, as well as any interaction effect in conjunction with environmental stringency. This analysis is also complicated by two competing effects. On the one hand, a rise in fixed costs raises costs, diverts resources away from productive output, and thereby raises average emissions intensity. This effect is captured by the $(1-\alpha_s)$ exponent on the tax in within-firm component of equation (3.7).

On the other hand, a rise in fixed costs raises costs for firms, which drives out less productive producers and raises the minimum productivity cut-off, thereby raising average productivity and lowering average emissions intensity. This effect is captured by the negative $\frac{1}{c}$ exponent on fixed costs in the within-firm component of equation (3.7). The general equilibrium effect reducing output and raising average emissions intensity will dominate only if $\frac{\sigma}{\sigma-1} > \frac{1}{c}$. Available evidence, presented above, suggests that σ is well above one, and the assumption that $\sigma - 1 < c$ ensures that both the distribution of productivity draws and the distribution of firm sales have finite variances.[18] When these assumptions hold, the general equilibrium effects reducing output will dominate the productivity gain effect, and thus a rise in fixed costs will tend to raise average emissions intensity. In addition, the fall in average emissions intensity, following a rise in environmental stringency, discussed above, will be magnified in sectors with higher fixed costs. In sectors facing higher fixed costs, the firms are, on average, larger and more productive. Changes to the average emissions intensity will be of larger magnitude when affected among a set of relatively larger firms. We summarize these findings in the following hypothesis:

Hypothesis 6: A rise in fixed costs raises average emissions intensity and magnifies the reductive effects of more stringent environmental policy.

Taken together, these six hypothesis form a set of testable predictions regarding the effects of environmental policy on emissions outcomes, in the presence of fixed costs, which we evaluate in the following section.

[18] See other examples in Helpman et al. (2004); Bernard et al. (2007b).

3.3 Data

We collect data for a panel of approximately four hundred and fifty US manufacturing sectors,[19] from 1990-2006. Our aim is to empirically evaluate the three hypotheses implied by equations (3.7) and (3.8) which relate fixed costs and environmental regulation to observed, aggregate emissions intensities. To test our hypotheses we require data on sector level pollution intensities, environmental regulation, and fixed costs.

We employ the National Bureau of Economic Research - Census for Economic Studies (NBER-CES) manufacturing database, described in Becker et al. (2013a). The database uses proprietary establishment level data from the Annual Survey of Manufacturers augmented from various sources to build an annual panel of production, factor input costs, productivity, sector-specific price indices, and various other industry level statistics. We use data on sales, price indices, labor and capital inputs, and TFP in our analysis.

Pollution emissions are published by the Environmental Protection Agency. The particular data source we employ is taken from the Risk Screening Environmental Indicators (RSEI) tool, based on establishment-level emissions reported in the Toxic Release Inventory (TRI) database. The TRI data differentiates the emissions data by medium of release (whether by air, water, landfill, incinerated, recycled, etc.) which the RSEI tool accounts for in order to accurately present data on actual toxic releases for each reporting establishment which is labeled as "ModeledPounds."[20] We aggregate the establishment data to the four-digit SIC level and merge with the NBER-CES data. Sector emissions intensities, the primary dependent variable of interest, are then constructed as the ratio of ModeledPounds to real output in each sector.

The TRI compiles reported pollution emissions by chemical for thousands of toxic chemicals regulated under the Emergency Planning and Community Right-to-Know Act (EPCRA). All U.S. facilities engaged in manufacturing, aspects of mining, some utilities, and other miscellaneous industry groups, and all federal facilities with more than ten employees that produce, process, or otherwise use more than a threshold level of a regulated chemical in a year[21] must report the quantity of all chemicals used over the course of the year and how any of those chemicals were disposed of, including air and water releases as well of off site management and recycling. The TRI have been widely used in economics literature, but they are an imperfect measure of emissions. In general, establishments whose holdings of toxic chemicals are below 10,000 pounds do not report their holdings of any chemicals, while

[19] Standard Industrial Classification (SIC4) codes 2000 - 3999.

[20] A recent update to the RSEI data relabeled this variable "PoundsPT."

[21] A common threshold is 10,000lbs but more toxic PBT chemicals have lower thresholds ranging down to 0.1-grams for dioxin.

establishments whose holdings exceed 10,000 pounds of any single chemical report their holdings of every chemical. There is also evidence that establishment may under-report their emissions in specific industries (Koehler and Spengler (2007)) and across all industries (de Marchi and Hamilton (2006)). The RSEI has been used in several studies to proxy for environmental performance of establishments, firms and communities.[22]

To explore the channels that our theory suggests underlie the aggregate emissions intensity outcomes, we employ a measure of the number of firms in each sector from the US Census, which we denote M, and a measure of average firm emissions intensity, which we denote $e(\tilde{\varphi})$. We construct the average emissions intensity measure using firm-level emissions data from the RSEI database, matched with sales and employment data in the National Establishment Time Series (NETS) database. The average emissions intensity is then simply a sales-weighted average of firm's emissions intensity,[23] where emissions intensity is the ratio of each firm's emissions to real output. Real output for each establishment is calculated using sector-specific price indices from the NBER-CES database.

The NETS is compiled from Dunn and Bradstreet data on creditworthiness by Walls and Associates. Dunn and Bradstreet collect establishment level information that is used to generate credit scores. These scores are required to receive government contracts and are regularly used to make decisions regarding payment terms, leasing equipment or office space and setting financing terms. The data are collected by surveying establishments, tracking payment histories with other establishments and through research in trade publications and news archives. Neumark et al. (2011) analyze the NETS data and compare them to data collected by the Current Population Survey (CPS) and the Current Employment Statistics (CES) Payroll Survey. They find that the NETS data on employment are of comparable quality to the CPS and CES.[24] They also use a media search to find reports of plant relocation. The NETS reflected around three-quarters of the moves that crossed a county or city line. That rate is similar to the rates found in Lexis-Nexis and Hoovers.com company location datasets.[25] Related environmental investigation by Cui et al. (2015) matches NETS

[22] See Holladay (2016) for an establishment level example from the trade and environment literature and Banzhaf and Walsh (2008) for analysis on the community level for examples.

[23] $e(\tilde{\varphi}_s) = \sum_{i \in s} \frac{sales_{is}}{Sales_s} e(\varphi_{is})$ where $sales_{is}$ represent firm sales, and $Sales_s$ represent sector sales.

[24] County-by-Sector comparisons of the data yielded correlation of 0.99 with CES and 0.95 with CPS.

[25] Haltiwanger et al. (2013) also discuss the quality of the NETS data and compare it to proprietary longitudinal data from the US Census LDB. They note that the NETS, with 14.7 million establishment in a typical year, appears to be comprised of some combination of employer and non-employer businesses but does not appear to contain the universe of employer and non-employer observations reported by the Census (an average of 7 million establishments per year with at least one employ, and an additional 15 million non-employer establishments). Further discussion of the merits of the NETS data can be found at youreconomy.org

data with the EPA's National Emissions Inventory environmental database to explore the environmental effects of exporting.

Table (E.1) summarizes the variables used in our analysis, and the environmental stringency and fixed costs measures are described in further detail below.

3.3.1 Environmental stringency measure

Environmental regulation data are notoriously difficult to obtain. We model a per-unit emissions tax, and thus our ideal measure would translate the suite of environmental regulation an industry faces into a per unit emissions tax, though, as discussed above, environmental regulation can take many forms. Existing literature has employed a number of different measures in an attempt to quantify the level of environmental regulation polluters face. In this section we introduce a new measure of environmental regulation that varies across industries and years. We provide evidence that suggests that this measure accurately captures the variation we seek to model. We believe that this measure represents a contribution to the literature on measuring environmental regulation.

Environmental stringency data

The environmental stringency measure we construct, relies on exogenous variation in regulation related to the Clean Air Act to proxy for the level of regulation faced by an industry. Numerous studies have taken advantage of Clean Air Act non-attainment status regulations to generate exogenous variation in the level of regulation facing polluters.[26] The Clean Air Act and its amendments authorize EPA to regulate polluters in counties where the ambient concentration of pollution exceeds the national ambient air quality standards (NAAQS) for six pollutants.[27] The parent state, of counties whose ambient concentrations exceed the NAAQS, must submit a cleanup plan to the EPA and polluting plants in the county are then subject to higher levels of environmental regulation.[28]

To construct a measure of environmental stringency, we hypothesize that sectors for which a larger share of output is located in counties subject to non-attainment status will be sectors that face a greater level of environmental stringency. Specifically, our measure,

[26] See Greenstone (2002, 2004) and List et al. (2003) among many others.

[27] The criteria air pollutants are Ozone, Particulate Matter, Carbon Monoxide, Nitrogen Oxides, Sulfur Dioxide and Lead.

[28] Existing plants releasing the pollutants that are measured above the threshold are subject to "reasonably attainable control technologies" and may be required to retrofit existing facilities. New plants are subject to "lowest achievable emissions rate" (LAER) which requires the installation of the cleanest existing technologies without regard to cost.

which we call "Non-Attainment Sales Share" (NASS), is given as the sum of establishment, n, sales in a given SIC4, s, in a given year, t:[29]

$$\text{NASS}_{st} = \frac{\sum_{st} (\text{sales}_{nst} | \text{NA} = 1)}{\sum_{st} (\text{sales}_{nst})} \tag{3.9}$$

where establishment level sales data are taken from the NETS database. We matched the NETS data, using establishment addresses, to EPA's historical records regarding whether the establishment's county was classified as being in non-attainment.

Two features of non-attainment status classification create variation that we exploit to control for the effect of environmental stringency in our estimation. The first is cross-sectional variation, which arises since only a sub-set of counties whose ambient pollution is above a pollutant threshold are subject to non-attainment. Thus, in any given period, industries differ in the regulation they face due to differences in industry location and concentration and differences in whether or not counties are classified by the EPA as being in non-attainment. The second source of variation is temporal, which generally arises as counties ambient air quality changes and they move in and out of attainment from year to year. This type of longitudinal variation allows for the inclusion of sector fixed effects to control for sector-specific characteristics that might otherwise confound our estimates of the environmental effect of regulation and fixed costs. The key advantage of this measure is that it allows us to exploit these sources of environmental regulation to evaluate the effect of regulation on emissions data measured by sector.

There are a few additional characteristics of this environmental regulatory measure that increase its credibility. First, since NAAQS are set at the national level, they are plausibly exogenous to local preferences or economic conditions affecting plants, sectors, and their parent counties that are classified. Second, over time as scientific understanding of the impacts of pollution emissions on human health has evolved the allowable concentrations have been periodically revised downward. These changes have forced counties into non-attainment status without any increase in ambient concentrations of pollution emissions, thus providing another source of exogenous variation over time. To visualize some of the variation we are able to exploit, we plot annual average NASS across our sample period in Figure (E.3). One notable feature of this plot is the sharp increase that occurs in 2004. This occurred due to the EPA's decision to increase the stringency of Ozone regulation by replacing the 1979 1-hour standard of 0.12ppm, with an 8-hour standard set at 0.08

[29]This measure includes counties for which "part" of the county and for which the "whole" county was listed in non-attainment, following Henderson (1996). In addition, since only plants that release the specific set of pollutants in non-attainment are subject to the increased regulation, this measure may overstate the amount of environmental regulation that plants are subject to. As such it provides an upper bound on the level of environmental stringency a sector faces.

ppm. Three states and dozens of industry plaintiffs quickly challenged the new standards which were not resolved until a decision by the US supreme court in 2001 after which the EPA finalized Ozone designation and implementation rules in 2004.[30] The resulting implementation increased the number of counties in non-attainment from 397 in 2003, to 806 in 2004. This type of exogenous variation, implemented from the national level and resulting in spatial and temporal variation in environmental regulation, is a key feature of the data that mitigates firm selection concerns. Finally, while the level of pollution emissions plays a role in ambient concentrations in a region there is considerable evidence that weather conditions and other exogenous shocks also play a substantial role, thus dampening concern that firms can influence regulatory stringency through strategic behavior.[31]

To further examine the quality of our measure of environmental stringency, we evaluate the concise model suggested by equation (3.5) by regressing annual sector emissions from the RSEI database, on annual sector sales, from the NBER-CES database, and our measure of environmental stringency, with all data in logs:

$$Z_{st} = \beta_0 + \beta_1 R_{st} + \beta_2 \tau_{st} + \delta_t + \varepsilon_{st} \tag{3.10}$$

We present results with and without sector fixed effects in Table (E.2). Each specification includes year fixed effects. We include sector fixed effects in column (2) to control for unobserved abatement technology, α_s, which may differ by sector. If the model is correct, and our measures are controlling for sector revenue and environmental stringency as we anticipate, then we expect β_1 to be near one and β_2 to be negative.[32] The estimated coefficients presented in Table (E.2) are consistent with our expectations. For example, results in column (1) suggest that a one percent increase in sector revenue is associated with a 0.89 percent increase in emissions, while a one percent increase in environmental stringency lowers emissions by 0.38 percent, *ceteris paribus*.[33] These results, both with and without sector fixed effects, give us confidence in the quality of our measure, suggesting that it is in fact controlling for important aspects of environmental stringency.

[30] See "Ozone & Health - A Timeline" (http://www3.epa.gov/ozonedesignations/1997standards/timeline.htm)

[31] See Greenstone (2002); Greenstone et al. (2012)

[32] We would only expect the estimated coefficient on the regulatory measure to also equal one if this measure was exactly and fully capturing an emissions tax as modeled. Given the challenges of measuring environmental stringency and costs, identified in related literature, our goal is to use the best proxy available in the estimation that follows.

[33] The coefficient on sector revenue less than one suggests a potential interaction with the environmental stringency measure which we explore more fully below.

3.3.2 Fixed cost measure

The measure of fixed costs we employee is calculated as the share of non-production workers per firm in each SIC4 sector, and follows Helpman et al. (2004) who estimate the impact of industry fixed costs on the decision of firms to export versus open horizontal multinational branches. They use the number of non-production workers per establishment as a firm-size and productivity independent measure of fixed costs of production. Non-production worker data is taken from the NBER-CES database, and the number of firms is gathered from the U.S. Census Bureau's Statistics of U.S. Businesses survey. To evaluate the quality of our fixed costs measure, we consider three propositions taken from the literature that studies various general equilibrium effects of heterogeneous firms and fixed costs. In standard models of industry equilibrium with firm entry and exit (e.g. Hopenhayn (1992) and Melitz (2003)), an increase in fixed production costs leads to a rise in the cut-off productivity,[34] and results in the following three effects:

1. A decrease in the number of firms
2. An increase in market concentration
3. An increase in average productivity

To examine these three channels, we take the number of firms in each four-digit SIC from the US Census. We measure market concentration, by constructing a Herfindahl-Hirschman Index (HHI), as the sum of market-share-squared for each firm, n, in a given sector, s: $\text{HHI}_s = \sum_{n=1}^{N} \left(\frac{\text{sales}_{ns}}{\sum_{n=1}^{N} \text{sales}_{ns}} \right)^2$. Thus, in a market with two firms that each have 50 percent market share, the HHI equals one half: $0.5^2 + 0.5^2 = \frac{1}{2}$. The HHI ranges from $1/N$ to one, where N is the number of firms in the market. The firm-level sales data used to construct the HHI are taken from the NETS database. Finally, the sector total factor productivity index (TFP) measure is taken from the NBER-CES database. We regress the measure of fixed costs on each of these three outcome variables in turn, using both a simple ordinary least squares specification and sector fixed effects. Each specification includes year fixed effects.

While other measures of fixed costs have been suggested in related literature which we consider in a later section, the results presented in Table (E.3) are consistent with each prediction regarding the expected effect of fixed costs, both with and without the inclusion of sector fixed effects and provide support for this measure as a proxy for firms' fixed production costs.

[34] A minimum productivity level firms must have profitably cover their fixed costs and remain in the market.

3.4 Identification and Results

In this section, we present the empirical model that we take to the data on fixed costs, environmental regulation, and aggregate emissions intensity. We then discuss potential identification concerns.

3.4.1 Empirical Specifications

Let s indicate a SIC4 sector, and t denote the year. To evaluate our first two hypotheses, related to equation (3.8) we implement the following reduced-form specification:

$$AEI_{st} = \beta_0 + \beta_1 \tau_{st} + \beta_2 f_{st} + \beta_3 \tau_{st} \cdot f_{st} + \delta_t + \varepsilon_{st} \tag{3.11}$$

The outcome variable of interest, AEI_{st} is the sector-level aggregate emissions intensity measure. The interaction term, $\tau_{st} \cdot f_{st}$, allows us to evaluate variation in the effects of environmental policy stringency and fixed costs across sectors.

In order to evaluate the various channels through which a change in environmental policy operates on aggregate emissions intensity, engendered in hypotheses 3 - 6, we estimate two additional specifications. To evaluate the reallocation effects of environmental policy, fixed costs and their interaction across firms, working through changes in the mass of firms we implement equation (3.11), but replace AEI_{st} with a number of firms measure, M_{st}, taken from the U.S. Census. To evaluate the effects of environmental policy, fixed costs and their interaction on within-firm outcomes, working through changes in average emissions intensity, we again implement (3.11), but replace AEI_{st} with average firm emissions intensity, $e(\tilde{\varphi}_{st})$.

3.4.2 Identification

The initial empirical identification of the effect of changing environmental stringency and fixed costs on aggregate emissions intensity is based on an ordinary least squares estimation, where the sources of variation in regulatory stringency, as measured by our index, are due to changes in policy and changes in ambient air quality (described above) that occur both across time and across sectors. The error term contains all additional factors influencing emissions intensity, including equilibrium relative wages, technology shocks, preference and distributional parameters. Our theory suggests that many of these factors that appear in equation (3.8), including relative factor returns to capital and labor and consumer preferences, are constant across across sectors for any given period, and thus all specifications will include year fixed effects, δ_t, to control for the evolution of these effects across our panel. There are a few potential threats to our strategy. One is that the relatively small share of

counties in non-attainment in a given period may limit our ability to identity a significant effect. As discussed above, variation in county non-attainment status translates into within and across sector variation in our regulatory index measure. While the majority of counties in the US remain in attainment status, these are also generally rural counties that do not have a substantial share of manufacturing activity. As a result the shares of manufacturing activity that are located in non-attaining counties in any given period is substantial, as evidenced by Figure (E.3).

A second threat to our identification, related to the credibility of our regulatory measure, is that our Non-Attainment Sales Share (NASS) measure uses sector sales share to provide weights, which may be endogenous to the level of regulation. If firms in some sectors are more likely to locate near one another for economies of scale efficiency gains, this type of agglomeration would also increase the likelihood of being regulated, which would tend to bias our estimates upwards, against finding a significant negative relationship, and thus our estimates can be interpreted as a lower bound measure of the full effect of environmental stringency in manufacturing sectors. Though we cannot rule out these types of sector-specific agglomeration effects, we can control for them–as well as other omitted sector-specific variables[35]–by including sector fixed effects. In these specifications, our estimates are identified only from variation within each sector over the sample period.

In addition, we present each set of specification results using data measured in both natural logs and levels. Taking seriously the model that forms the basis for our empirical inquiry, given in equations (3.7) and (3.8), a log-linear specification has four significant advantages. First, it will tend to make our coefficients easy to interpret, as elasticities. Second, it will link some of the coefficient estimates directly to parameters in the model. Third, it will cleanly separate the non-estimated parameters and variables contained in (3.7) and (3.8) from the variables of interest, allowing them to be more plausibly controlled for with fixed effects. Fourth, since the emissions intensity measure is heavily right skewed, similar to a log-normal distribution, as can be seen in Figure (E.2), log-linearizing the specification mutes the outsized effect of the relatively small number of extreme values. On the other hand, if the model is correct, log-linearizing equations (3.7) and (3.8) will also remove, and thereby mask, the predicted interaction between environmental policy and fixed costs. In other words, while the magnitude of the effect of environmental stringency on AEI is predicted to vary with the level of fixed costs, the model predicts the percentage change, for small changes, to be invariant to differences in fixed costs. We discuss the results from these various empirical approaches below.

[35]For example, differences in the production or abatement technologies employed, the quality of data reporting, or other unobserved factors correlated with our model variables

3.4.3 Interpreting the Results

The theory emphasizes the point that more stringent environmental policy induces multiple general equilibrium effects that serve to lower AEI (Hypothesis 1), and that fixed production costs systematically affect firms' heterogeneous choices and magnify the effects of environmental policy (Hypothesis 2). Thus the model predicts a negative coefficient on our environmental stringency measure, a positive coefficient on the fixed cost measure, and a negative coefficient on their interaction. The relevant null hypothesis for equation (3.11), regarding firms extensive-margin decision, is that $\beta_2 = \beta_3 = 0$, which would imply that endogenous entry and average productivity are insignificant factors influencing emissions intensity, and that a representative-firm model will accurately capture the effects of more stringent environmental policy on the environment. Of course, with the inclusion of the interaction term in the specification, the marginal effects of each variable depend on the value of the modifying variable. Consequently, for each set of results we also present average marginal affects that are calculated using the values of the modifying variables in our data set.

Our theory points to two channels driving aggregate emissions intensity outcomes. The first works through changes in the mass of firms. The predictions embodied in hypotheses 3 and 4 are a negative coefficient on both the environmental stringency measure and the measure of fixed costs. Their interaction is predicted to be positive.

Finally, the predictions embodied in hypotheses 5 and 6 are a negative coefficient on the environmental stringency measure, a positive coefficient on the fixed cost measure, and a negative effect on the interaction term.

3.4.4 Results

Tables (E.4), (E.5), and (E.6) each present results in the same format. In each table, columns (1) - (4) present results with data measured in levels, while columns (5) - (8) present the same analysis on data measured in natural logs. Columns (1) and (5) present results from a an ordinary least squares while columns (2) and (6) augment these results by including sector fixed effects and clustering the standard errors by sector. The level and log specification results are followed by the calculated average marginal effects (AME).

Aggregate Emissions Intensity

Table (E.4) presents results from the specification in equation (3.11) in which aggregate emissions intensity is regressed on environmental stringency (Enviro. Reg.$_{NASS}$), fixed costs (FC), and their interaction.

Consistent with the predictions of our model, the negative coefficient on Enviro. Reg.$_{NASS}$ in column (1) indicates that more stringent environmental regulation, due to increased exposure to non-attainment regulations, decreases AEI, *ceteris paribus*, while higher fixed costs increase AEI, *ceteris paribus*. Finally, the interaction of fixed costs with environmental regulation is also negative as predicted, suggesting that higher fixed costs do indeed magnify the effects of environmental policy. Due to our use of panel data, we cluster all heteroskedasticity-robust standard errors at the SIC4 level. Clustering the standard errors in this way results in relatively large standard errors and a general lack of precision on many of the estimated coefficients.

We emphasize a *ceteris paribus* interpretation for the first two coefficient estimates because, with the inclusion of the interaction term, a *ceteris paribus* interpretation of each coefficient implies that the value of the interaction term is zero. In other words, the results in column (1) suggest that a one percentage point rise[36] in the share of sector sales subject to non-attainment regulations (Enviro. Reg.$_{NASS}$) lowers AEI by 9.17 pounds *if* fixed costs equal zero.[37] Since nearly all sectors instead incur positive fixed costs of varying degrees in each year of our panel this interpretation may not be particularly meaningful. To address this issue, columns (3) and (4) of Table (E.4) report the AME for each of the two independent variables, where the marginal effects are calculated using actual observed values of the interaction variable. The coefficient on Enviro. Reg.$_{NASS}$ in column (3) indicates that, on average, a one percentage point increase in the share of sector sales subject to non-attainment lowers AEI by 12.4 pounds. Columns (2) and (4) of Table (E.4) report coefficients, and corresponding AME, from a fixed effects regression which augments the results presented in columns (1) and (3) by including SIC4 fixed effects. These results are inline with those presented in columns (1) and (3), with identical signs. While not overturning the results in columns (1) and (3), the coefficients are smaller and are estimated with less precision.

The Log-Log results presented in columns (5) - (8) explain a substantial amount of observed variation, as measured by R^2, and are also largely consistent with the theoretical predictions except with regard to the interaction effect. However, while the model predicted

[36]Because the environmental stringency measure is a share, ranging from 0 to 100, of the share of a a sector's output that is produced in counties in Non-Attainment, the a one unit increase in stringency can be interpreted as one percentage point increases in stringency.

[37]Note that although our environmental stringency measure is not measured in natural logs, since it represents a share ranging from zero to one, the coefficient estimates can be interpreted as elasticities.

that a log-linear specification would eliminate the interaction effects, the interaction is significant and positive in column (6), suggesting that our simplified model may not be fully capturing the complex mechanism that is actually at work between environmental policy and fixed costs.[38] The average marginal effects reported in columns (7) and (8) are of similar magnitude and imply that a one percent increase in environmental stringency decreases aggregate emissions intensity by roughly a quarter of a percent.

Taken together, these results provide evidence that changes in environmental policy are an important factor reducing observed aggregate emissions intensity, and that the environmental effects of changes in environmental policy are systematically affected by the presence of fixed costs. To explore the underlying channels that the theory points to as the drivers of these aggregate results we turn now to examine the effects of environmental policy and fixed costs on the mass of firms and average emissions intensity.

Mass of Firms

Table (E.5) presents results from our analysis using the specification in equation (3.11) in which the dependent variable is replaced by a measure of the number of firms in each SIC4 sector and regressed on environmental stringency , fixed costs, and their interaction.

Our first concern are the positive and significant estimated average marginal effects on Enviro. Reg.$_{NASS}$, reported in columns (3) and (7), which are inconsistent with the predictions of the model. However, we suspect that this may be due to omitted systematic agglomeration tendencies across sectors that influence firms' choice of whether and where to enter a market, and that the most sensible interpretation of these positive coefficients is that they are due, in part, to sector-specific endogeneity. Systematic agglomeration characteristics of some sectors would tend to be positively correlated with the number of firms in a sector–since agglomeration by these firms would serve as a source of efficiency gain, reducing production or distribution costs, and making entry more profitable. These same agglomeration characteristics would also be positively correlated with our measure of environmental stringency, since larger concentrations of polluting firms would increase the likelihood of a county falling into non-attainment and thereby increasing environmental stringency. Omitting this type of sector characteristic would, thus, lead to positive bias in the estimated effect of environmental stringency. To control for these types of sector-specific

[38] For example, in contrast to the autarky model developed here, Bernard et al. (2007b) develop a two-sector trade model in which changes in domestic policy result in complex general equilibrium effects on price indices and relative prices that affect firm entry and output decisions. In that framework, changes in environmental policy and fixed costs would continue to interact even if the model were log-linearized. Our result could be identifying the fact that environmental policy changes also affect firms international competitiveness which further influences their entry, exit, and production decisions.

characteristics, that may vary substantially across sectors but little across time, we also present results that include sector fixed-effects in columns (2) and (6). In this fixed-effects specification, the coefficient estimates are identified off of variation within-sectors over time that is plausibly exogenous–due to policy adjustment at the national level, weather variation, etc. These results are consistent with the model predictions, and generally significant, though the AME of environmental stringency in column (4) lacks precision.

Regarding the potential of an interaction between environmental policy and fixed costs, there is little evidence of a strong interaction effect working through the extensive effects of firms' entry and exit decisions. A final observation worth noting is that, estimating a Log-Log version of the across-firm component of equation (3.7), the coefficient on the the environmental policy measure can be interpreted as the technology parameter, α, that governs the cost share firms allocate to environmental expenditures. The results in column (8) suggest that this value is approximately equal to 0.047.[39] Thus, a one percent rise in environmental stringency is expected to reduce the number of firms by 0.047 percent. Fixed costs, on the other hand, have a much larger effect, with results in column (8) showing that a one percent increase in a sector's fixed costs will reduce the number of firms by 0.62 percent. Taken together, these results provide evidence that is generally consistent with our theoretical framework. Changes in environmental policy and fixed costs are significant factors reducing the observed number of firms, though whether these variables interact through this channel remains inconclusive.

Average Emissions Intensity

Finally, we turn to examine the within-firm component of equation (3.7) using average firm emissions intensity. Table (E.6) presents results from the specification in equation (3.11) where the dependent variable is replaced by the average emissions intensity of firms in each SIC4 sector and regressed on environmental stringency, fixed costs, and their interaction.

The results in columns (1) - (4) are generally supportive of the model predictions. All of the coefficient estimates–including the interaction effects and the average marginal effects–are consistent with the model predictions, but they are all imprecisely estimated. In contrast, the results in columns (5) - (8) are strongly supportive of the model predictions. Columns (7) and (8) clearly convey support for the hypothesis that more stringent environmental policy lowers firms' emissions intensity, while higher fixed costs result in higher average productivity among firms in a sector, thereby lowering the emissions intensity of firms on

[39] Pursuing a different estimation strategy, Shapiro and Walker (2015) estimate an average value for α of 0.011; Our estimate is larger but of the same order of magnitude.

average. In addition, the interaction effect also lacks significance when taking logs, as the model predicts.

Taken together, the results from Tables (E.4), (E.5), and (E.6) provide substantial support for our theoretical framework. The model appears to perform particularly well in describing the within-firm effects of environmental policy and fixed costs.

3.5 Robustness

Several potential concerns regarding our approach warrant further consideration. The first relates to our measure of fixed costs. To check the relative quality of our preferred fixed costs measure, we examined several other measures used in related literature. Each of these measures is summarized in Table (E.7).

3.5.1 Fixed Costs

The first measure, FC, is the measure used in our baseline results and is repeated here for the sake of comparison.[40] The second measure, FC2, the "Share of non-production workers per firm," is calculated as the ratio of non-production workers to to total employment, divided by the number of firms in each sector. This measure follows Syverson (2004) who argues that this measure proxies for the amount of overhead labor required by the industry technology and thus is a fixed cost explicitly tied to production rather than entry. Constructing FC2 as a proportion also removes scale effects across industries. The third measure we consider, FC3, "Capital Resalability Index," is the share of used capital investment in total capital investment at the four-digit SIC aggregate level. This measure is taken from Balasubramanian and Sivadasan (2009)[41] who argue that a higher share of used capital investment indicates a more flexible resale market, and thus capital investment costs are not completely sunk upon entry. Since, as in related heterogeneous firm models (e.g. Hopenhayn (1992); Melitz (2003); Syverson (2004)), the firms' entry decision is made based on the ratio of fixed entry to fixed production costs, a relative increase in fixed cost has the same effect as a relative decrease in sunk entry costs. Thus, they argue that "in general, the capital resalability index could be viewed as either an (inverse) measure of the sunkenness of investments or a (direct) measure of fixed costs" (p. 550). The major drawback to this measure is that it is currently only available for Census years 1987 and 1992 and thus only

[40] Recall that our preferred FC measure is calculated as the ratio of non-production workers in each sector, taken from the NBER-CES database, to the number of firms in each sector, reported by the US Census Bureau's Statistics of U.S. Businesses survey.

[41] The authors have generously made their measure publicly available.

overlaps our data for a single year and limiting our ability to exploit the benefits of our panel.

To evaluate the merits of each of these measures we regress each of them on the three measures described previously in the data section: (a) the number of firms in a sector, (b) market concentration, measured by a Herfindahl-Hirschman Index (HHI), and (c) a total factor productivity (TFP) index. Higher fixed costs are expected to lower the number of firms operating in a sector, raise the market concentration, and raise average productivity of surviving firms. The results of this comparison, presented in Table (E.8), demonstrate that our preferred measure, FC (the number of non-production workers per firm), is the only one that provides significant results that are consistent with the predictions regarding the effects of fixed costs on each of the three outcomes. This is the first comparison of this kind of which we are aware.

3.5.2 Environmental Stringency

A second potential concern relates to our measure of environmental stringency. To check the relative quality of our environmental measure we devise a second measure of environmental regulation that we estimate using data from the EPA's Pollution Abatement Cost and Expenditure (PACE) survey. Unlike related literature that simply includes abatement expenditure, or abatement expenditure per sales or materials cost, our measure relies on our theoretical framework to provide a structure from which we estimate an implicit environmental tax, controlling for the influence of other market factors, including capital and labor costs, that affect firms' abatement choices. The details regarding how this measure is derived and estimated are described in the appendix. The drawback to this measure is that, due to the choice by the EPA and U.S. Census to discontinue the survey, it only overlaps our panel for 5 years, from 1990-1994. Following a similar approach to that used with our preferred NASS measure, we first implemented equation (3.5) using this alternative measure of environmental stringency. The results, presented in Table (E.9), both with and without sector fixed effects in columns (1) and (2), respectively, suggest that this alternative measure also provides a reasonable measure of environmental stringency, though the coefficient in column (1) is imprecisely estimated.

We follow up the baseline results by repeating the regression analysis presented using our preferred measure of regulation, above. These results, presented in Table (E.9) are generally consistent with the predictions of the model. The only significant exception is the negative coefficient estimate on the interaction between fixed cost and environmental stringency in the Log-Log specification presented in column (8), which suggests, as discussed in the baseline

specification, that the model may not be fully capturing the complex ways that fixed costs and environmental policy interact in general equilibrium. Thus, while inconsistent with a strict interpretation of the model's structure, we believe this suggests an opportunity for future work to be done to better understand how changes in environmental stringency and its interaction with fixed costs affect firms decisions and ultimately affect aggregate environmental outcomes.

3.5.3 Capital Intensity

Finally, the theoretical model culminating in equation (3.7) sets up the possibility that sector technologies governing firms' choices of factor intensities–represented by the α and β technology parameters–vary across sectors. Related to this, recent environmental literature, including Kahn (1999); Cole et al. (2005); Cole and Elliott (2005), has shown evidence that capital intensity is a key factor related to emissions intensity and generally find that capital intense sectors are also emissions intense. Further, although our model assumes static fixed technological factors, it could be that different sectors' factor intensities vary over time, and interact with the changes in fixed costs and environmental regulation. If this is the case, then our inclusion of sector-specific fixed effects will not adequately control for these changes which may confound our estimates of the environmental effects of fixed costs and environmental policy. To address this potential concern we augment the specification in (3.11) to include a measure of capital intensity (K/L) that we interact with our measures of environmental stringency and fixed costs. The capital intensity measure is calculated as the ratio of capital investment to employment payroll costs taken from the NBER-CES database.

The results are presented in Table (E.10). Columns (1) - (4) present results in levels. Columns (1) and (2) present the results both with and without sector fixed effects (respectively), and columns (3) and (4) present the corresponding average marginal effects. Columns (5) - (8) repeat this analysis with the data measured in logs. Results in each column are consistent with findings in related literature that capital intense industries are also emissions intense, though the average marginal effect of capital-intensity in columns (4) and (8) are imprecisely estimated. The estimated coefficients on the measures of fixed costs, environmental stringency, and their interaction are similar to those presented in the baseline results in Table (E.4). The only statistically significant sign changes on the estimated average marginal effects, occurs on the fixed cost measure in column (7). In addition, the model's goodness of fit, as measured by R^2 , does generally increase with the inclusion of capital intensity. Thus, while capital intensity does appear to be an important factor influencing

observed AEI, its inclusion does not appear to significantly change the estimated effects of fixed costs and environmental policy on AEI over time.

3.6 Conclusion

The remarkable fall in pollution emissions from manufacturing over the past thirty years has been the focus of considerable attention, both by policy makers and the economics literature. In this paper we introduce a new heterogeneous firm model of polluting industries. The model captures some unique stylized facts in the data, but also allows us to decompose the effect of environmental regulation on pollution emissions and polluting firms across industries. The model highlights the point that environmental regulation and differences in fixed costs of production are both important factors that interact to influence firms extensive entry and exit decision as well as their intensive decision regarding what technology and what factor intensities to employ in production. The empirical work contributes three unique analytical results. First, our results provide a first look at the role of fixed costs and environmental regulation on emissions outcomes, motivated by a theoretical foundation built on heterogeneous firms. Second, our analysis provides the first results documenting the effect of a new measure of environmental regulation on emissions outcomes. The measure adds to a small but growing list of measures of environmental stringency that link exogenous variation over time and across space to emissions outcomes measured at the sector level. Finally, our results show how, and through what channels, environmental policy and fixed costs interact to influence observed changes in aggregate emissions intensity through firms' extensive entry and exit decisions and their intensive decisions regarding technology and abatement investment.

The results have implications for questions of environmental policy design by showing that the form of environmental regulatory costs matters significantly for their impact. In our baseline model environmental regulation is modeled as a marginal tax, and we assume that firms' abatement and entry decisions require the same factor intensity as production. Relaxing that assumption introduces a new channel through which environmental regulation can affect industry emissions. For example, introducing an environmental regulation through a technology standard, such as a smokestack scrubber, may raise the fixed costs of entry or production or both. Which type of regulation is enacted, or which one dominates, has important implications for the the average productivity in an industry as well as aggregate environmental outcomes. Future work should address the implications of this assumption on the results presented here and the degree to which policy works through one or more of these channels.

Our results have focused on toxic pollution emissions reported in the Toxic Release Inventory from U.S. manufacturing firms. Of course, this approach would be effective in evaluating the impact of environmental regulation on other types of pollutants and in other countries. Any country and industry which produces data on pollution emissions, environmental regulatory stringency, and fixed production costs could in principal be evaluated using the same framework. Other environmental policy design questions including which industries are most sensitive to environmental regulation or which industries would provide the most pollution reduction from a given increase in regulatory stringency can also be informed by these results.

The combination of the theoretical results and the support provided by our empirical analysis lead us to conclude that policy evaluation and design should account, both, for the intensive response of firms, via adjustment to abatement techniques and production, and the extensive response as firms enter and exit in response to changing fixed costs and regulation. The results highlighting the role of environmental policy in firms entry and exit decisions in addition to their abatement and technology investment decisions, provides a caution for policy makers to carefully consider the competitive effects of policy changes and regulation. Whether the regulatory costs come in the form of a higher fixed cost or a higher variable cost has important implications for employment and output effects of the policy change that should be carefully considered by anyone concerned with national welfare.

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Appendix

Appendix A

Chapter 1 Figures and Tables



Figure A.1: US Manufacturing Real Output, Imports, Exports, and Emissions

Note: The emissions measure is an aggregate measure of the pounds of emissions released by establishments, published in the EPA's RSEI database. Import and export data are an update of data used in Schott (2008). Real output is calculated using sales and price indices published in the NBER-CES database described by Becker et al. (2013a).

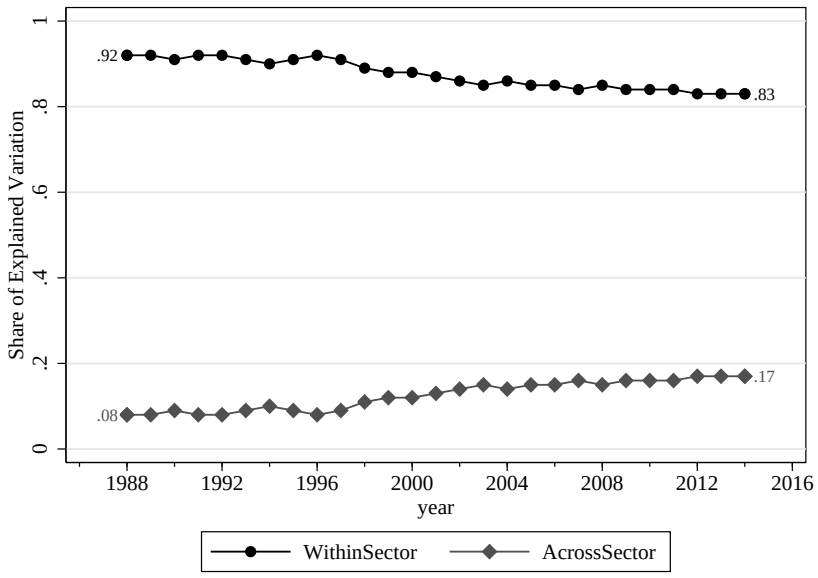


Figure A.2: Variation in Emissions Within and Across SIC2-Sectors (RSEI)

Note: The emissions data used for this figure are taken from establishment-level data released in the EPA's RSEI database. The top line plots the relative share of changes in this measure of emissions that is explained by variation within sector groups. The lower line plots the relative share of changes in emissions explained by variation within sector groups. Sector groups are defined by their two digit SIC code.

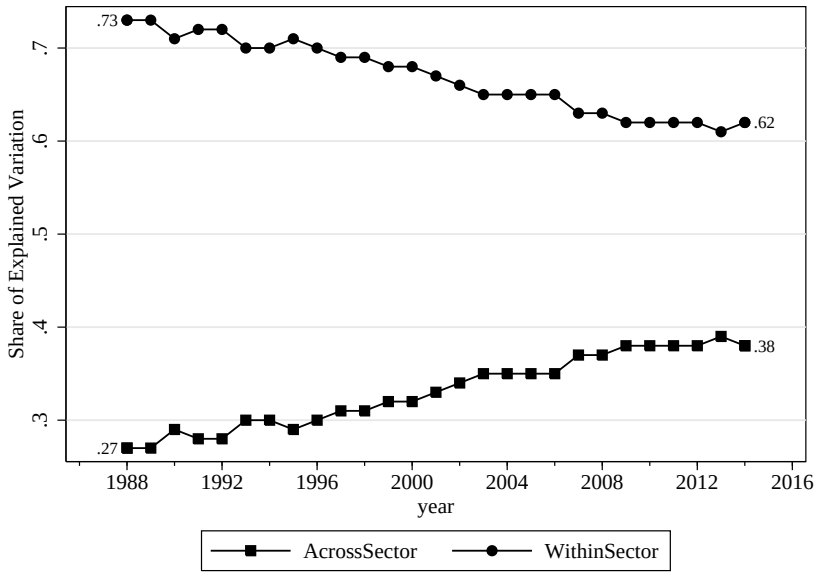


Figure A.3: Variation in Emissions Within and Across SIC4 Sectors (RSEI, Manufacturing)

Note: The emissions data used for this figure are taken from establishment-level data released in the EPA's RSEI database. The top line plots the relative share of changes in this measure of emissions that is explained by variation within sector groups. The lower line plots the relative share of changes in emissions explained by variation within sector groups. Sector groups are defined by their four digit SIC code.

Table A.1: Sample Comparison: RSEI (Pounds)

	Pounds		Log Pounds	
	Matched Sample	Full NETS Sample	Matched Sample	Full NETS Sample
Mean	75,553.2	80,628.8	8	7.9
Std. Dev.	460,948.6	612,422.9	3.2	3.3
Median	5,999.453	5,400	8.7	8.6
Min	7.0E-04	7.50E-08	-7.3	-16.4
Max	45,500,000	110,000,000	17.6	18.5
Obs.	151,167	377,743	151,167	377,743

The first two columns compare the sample emissions (measured in pounds) statistics for the matched RSEI-NETS sample and the full RSEI sample. The second two columns compare the sample log-pounds statistics.

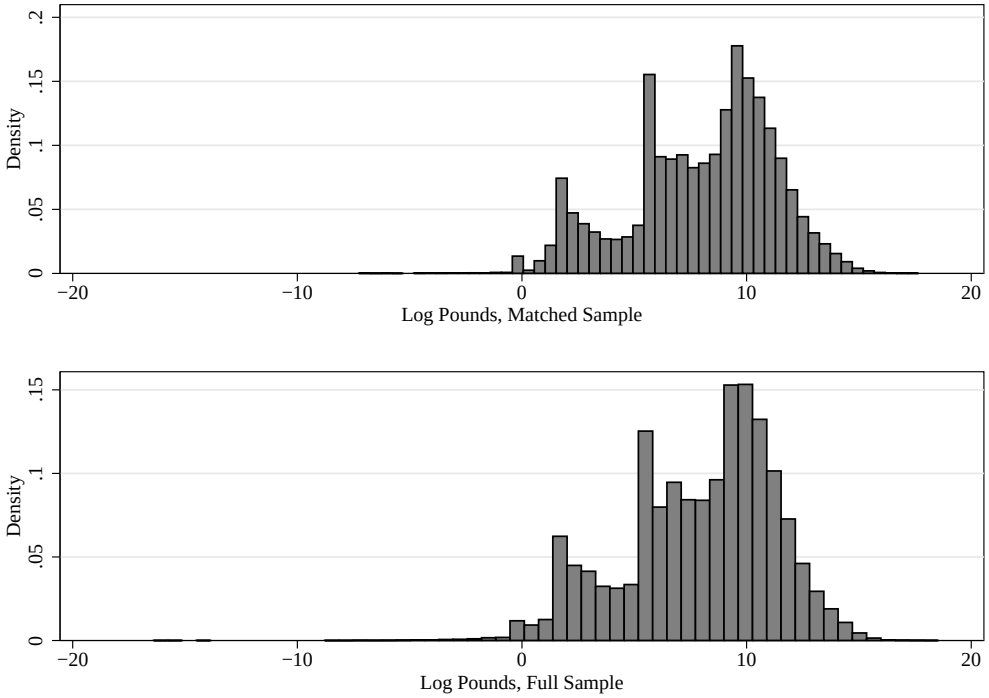


Figure A.4: Sample Comparison: RSEI (Pounds)

Note: The log-emissions data for the top panel of this figure are taken from matched RSEI-NEI establishment-level data set described in the text. The distribution in the lower panel is based on the log-pounds of manufacturing establishments (SIC2 20-39) from the full RSEI sample.

Table A.2: Sample Comparison: NETS (Sales and Employment)

	Employment		Log Employment		Sales		Log Sales	
	Matched	Full NETS	Matched	Full NETS	Matched	Full NETS	Matched	Full NETS
Mean	301.1	51.9	4.8	2.7	40.7m	6.4m	16.5	14.1
Std. Dev.	703.8	228.6	1.4	1.3	124m	49.7m	1.5	1.6
Median	125	12	4.8	2.5	14.6m	1m	16.5	13.8
Min	1	1	0	0	3775	0	8.2	0
Max	27,000	30,000	10.2	10.3	9.65b	21b	23	23.8
Obs.	151,167	2,447,191	151,167	2,447,191	151,167	2,447,109	151,167	2,447,095

The first two columns compare the sample employment statistics for the matched RSEI-NETS sample and the full NETS sample. The second two columns compare the sample log-employment statistics. The third and fourth columns compare the sample sales statistics and the final two columns compare the sample log-sales statistics.

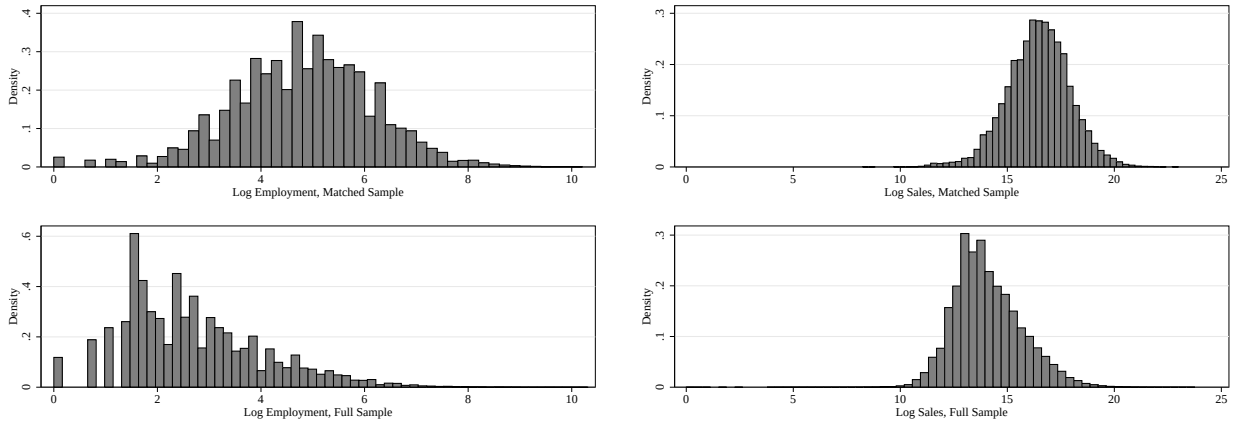


Figure A.5: Sample Comparison: NETS (Sales and Employment)

Note: The log-employment data and log-sales for the top panel of this figure are taken from matched RSEI-NEI establishment-level data set described in the text. The distributions in the lower panel are based on the log-employment and log-sales of manufacturing establishments (SIC2 20-39) from the full NETS sample.

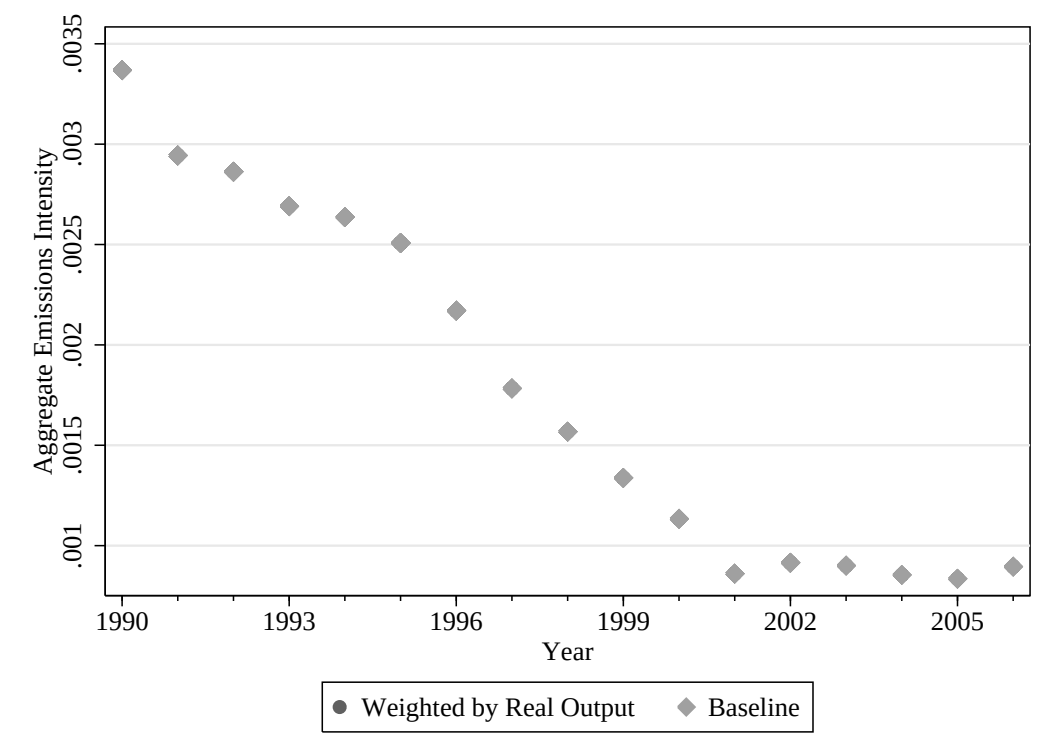


Figure A.6: Annual Aggregate Emissions Intensity

Note: The figure presents the evolution of aggregate emissions intensity over time. The "Baseline" aggregate emissions intensity is calculated as the ratio of total annual ModeledPounds (from the matched RSEI-NETS database) to real total annual output (calculated from establishment sales in the matched RSEI-NETS sample, weighted by price indices from the NBER-CES database). This measure is exactly replicated by calculating aggregate emissions intensity as the weighted-sum of establishment emissions intensity, using the same data set, where weights are given by each establishment's real-output share in each year.

Table A.3: Market Share and Entry Rates by Entrants and Exiters (RSEI)

	Market Share		Entry and Exit Rates			
	RSEI		RSEI		US Census	
Year	Entrants	Exiters	Entrants	Exiters	Entrants	Exiters
1990		8.5		13.8	10.9	8.9
1991	6.5	7.4	10.7	10.5	9.6	9.5
1992	6.1	9.6	9.5	12.3	9.1	9.6
1993	6.3	8.6	12.1	11.1	9.5	8.8
1994	5.9	8.3	9.7	14.3	9.6	8.7
1995	6.6	8	9	12.2	9.6	8.4
1996	4.7	8.7	10.2	14.5	9.1	8.7
1997	5.9	8	10.1	10.1	8.9	9
1998	7.8	5.7	10.3	9.8	8.8	8.8
1999	5.9	6.8	9.2	9.1	8.1	9.1
2000	10.3	9.8	10.4	11.5	8.3	9.4
2001	4.8	6.8	9	10.7	7.8	9.6
2002	7.9	4.7	9.2	9.9	8.4	11
2003	4.8	4	7.9	9	7.7	8.7
2004	3.9	5.3	8.5	9.6	7.8	8.3
2005	3.2	4.7	7.2	12.1	7.8	7.7
2006	1.8		6.2		8.2	8
Mean	5.8	7.1	9.3	11.1	8.6	9

For the RSEI sample, entry and exit are defined as occurring when an establishment begins reporting and stops reporting (respectively) to the TRI. Entry and Exit rates for the US Census data are publicly available in the Business Dynamics Statistics database. Market Share is the ratio of sales by establishments in each category to total sales in each year. Entry and Exit Rates are the ratio of entering and exiting establishments (respectively) to total establishments in each year. The matched RSEI and NETS sample runs from 1990 - 2006. Thus, all observation in 1990 are "Entrants" and all observations in 2006 are "Exiters." The 100-percent shares were replaced by blank cells for that dataset.

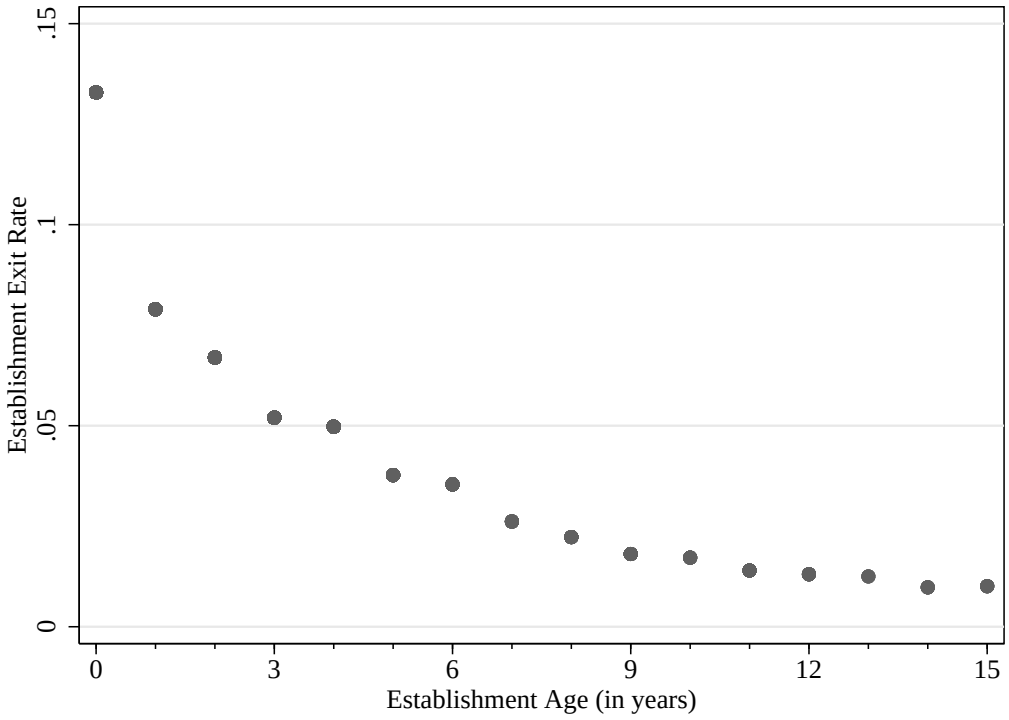


Figure A.7: Exit Rate by Establishment Age: RSEI

Note: This figure plots the relationship between establishment age and establishment exit rate, using data from the matched RSEI-NETS data set. Entry and exit are defined as occurring when an establishment begins reporting and stops reporting (respectively) emissions to the EPA under the TRI reporting requirements.

Table A.4: Change in Aggregate Emissions Intensity by Channel

Year	Surviving Establishments	Entering Establishments	Exiting Establishments	All Establishments
1991	-16.73	-3.99	7.25	-13.47
1992	-6.93	-1.32	5.46	-2.79
1993	-13.39	-1.19	8.41	-6.18
1994	-5.68	-2.68	6.32	-2.04
1995	-7.68	-4.43	7.09	-5.02
1996	-20.07	-0.93	6.6	-14.4
1997	-21.7	-2.8	4.91	-19.6
1998	-16.78	-3.14	7.06	-12.87
1999	-15.74	-2.77	2.66	-15.85
2000	-19.57	-2.49	5.59	-16.47
2001	-35.15	0.03	7.72	-27.41
2002	9.47	-3.91	0.51	6.08
2003	-1.62	-1.67	1.75	-1.55
2004	-3.64	-1.56	-0.07	-5.27
2005	-5.47	-0.51	3.69	-2.28
2006	7.67	0.64	-1.33	6.98

The second column presents the total annual percentage change in aggregate emissions intensity for surviving firms, in each year relative to 1990. Column three presents the change for entrants, column four presents the change for exiting firms, and the final columns presents the aggregate change (which is equivalent to the sum across each of the three channels). Entry and exit are defined as occurring when an establishment begins reporting and stops reporting (respectively) to the TRI.

Table A.5: Change in Aggregate Emissions Intensity By Surviving Establishments

				Share (in percent)	
Year	Surviving Establishments	Within Establishment	Across Establishments	Within Establishment	Across Establishments
1991	-16.73	-23.77	7.05	-77	23
1992	-6.93	-16.92	9.99	-63	37
1993	-13.39	-4.82	-8.57	-36	-64
1994	-5.68	3.26	-8.94	27	-73
1995	-7.68	-60.84	53.16	-53	47
1996	-20.07	36.98	-57.05	39	-61
1997	-21.7	-16.97	-4.73	-78	-22
1998	-16.78	-11.77	-5.01	-70	-30
1999	-15.74	-17.83	2.09	-89	11
2000	-19.57	7.63	-27.21	22	-78
2001	-35.15	-19.57	-15.59	-56	-44
2002	9.47	71.2	-61.73	54	-46
2003	-1.62	25.78	-27.4	48	-52
2004	-3.64	2.82	-6.47	30	-70
2005	-5.47	-9.76	4.29	-69	31
2006	7.67	-3.82	11.5	-25	75

The second column presents the total annual percentage change in aggregate emissions intensity for surviving firms, in each year relative to 1990. Columns three and four decompose that into the change due to within-establishment technique adjustments and across-establishment reallocation. The final two columns present the within and across establishment changes as the share of the total change (in absolute value) of the two channels, to give an additional sense of the relative magnitudes.

Table A.6: Market Share and Entry Rates by Entrants and Exiters (NETS)

	Market Share			
Year	Entrants	Exiters	Entry Rate	Exit Rate
1990		0.7		0.9
1991	0.8	0.9	0.9	0.9
1992	1.4	1.2	1.4	0.9
1993	3	0.8	4.7	1
1994	1.3	0.4	1.9	0.7
1995	1.6	0.7	2.1	1.1
1996	1.2	1.4	2.4	1.9
1997	2.3	0.4	2.8	0.8
1998	2.3	0.5	2.3	0.8
1999	3.2	0.9	2.1	0.9
2000	6.3	2.6	3	0.9
2001	1.6	0.7	2.8	1
2002	1.4	0.9	2.5	1.1
2003	1.6	1.1	2	1.6
2004	1.4	1.5	2.2	1
2005	0.5	1.5	1.9	1.5
2006	0.4		1.5	
Mean	1.9	1	2.3	1.1

Entry and exit are defined by a firstyear and lastyear indicator (respectively) in the NETS database. Market Share is the ratio of sales by establishments in each category to total sales in each year. Entry and Exit Rates are the ratio of entering and exiting establishments (respectively) to total establishments in each year. The sample runs from 1990 - 2006. Thus, all observation in 1990 are "Entrants" and all observations in 2006 are "Exiters." The 100-percent shares were replaced by blank cells.

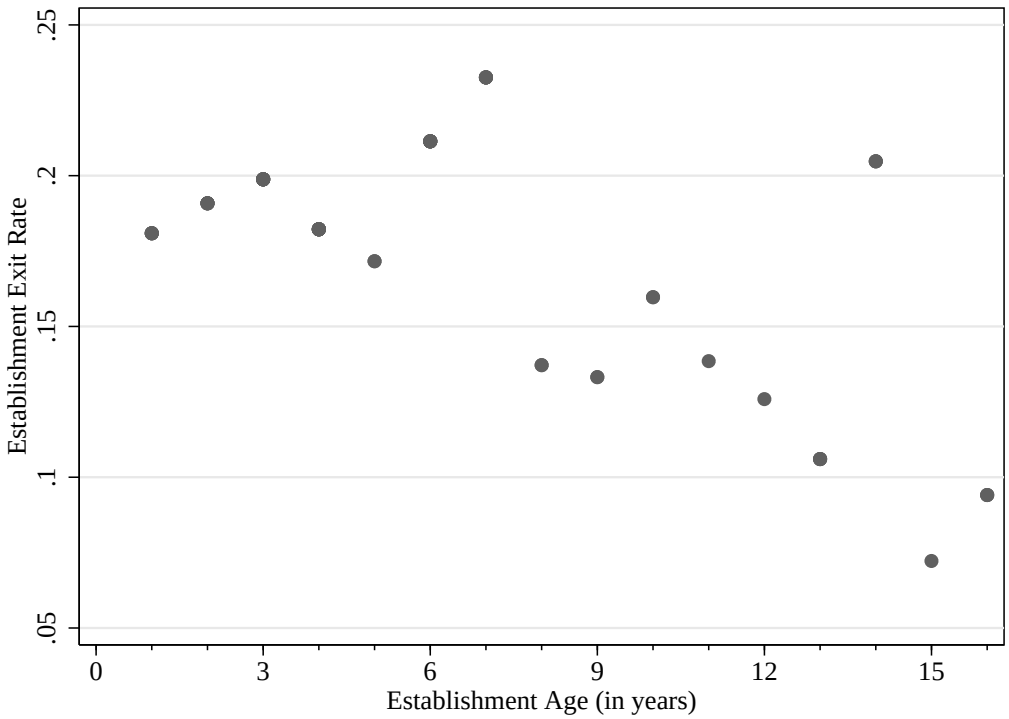


Figure A.8: Exit Rate by Establishment Age: NETS

Note: This figure plots the relationship between establishment age and establishment exit rate, using data from the matched RSEI-NETS data set. Entry and exit are defined by a "firstyear" and "lastyear" indicator (respectively) in the NETS database.

Table A.7: Sales Share and Entry Rates by Entrants and Exiters (NETS)

Year	Surviving Establishments	Entering Establishments	Exiting Establishments	All Establishments
1991	-13.81	-0.16	0.5	-13.46
1992	-2.65	-0.58	0.44	-2.79
1993	-7.31	0.48	0.65	-6.18
1994	-3.04	0.86	0.14	-2.04
1995	-4.63	-0.59	0.2	-5.02
1996	-15.25	0.69	0.16	-14.4
1997	-19.06	-0.56	0.02	-19.6
1998	-13.34	0.32	0.15	-12.87
1999	-13.84	-1.2	-0.81	-15.85
2000	-17.58	0.6	0.5	-16.47
2001	-32.09	2.31	2.38	-27.41
2002	6.77	1.9	-2.59	6.08
2003	-1.8	0.82	-0.57	-1.55
2004	-4.41	0.22	-1.08	-5.27
2005	-4.48	1.36	0.83	-2.28
2006	6.2	1.52	-0.73	6.98

Values represent percentage-point changes in aggregate emissions intensity.

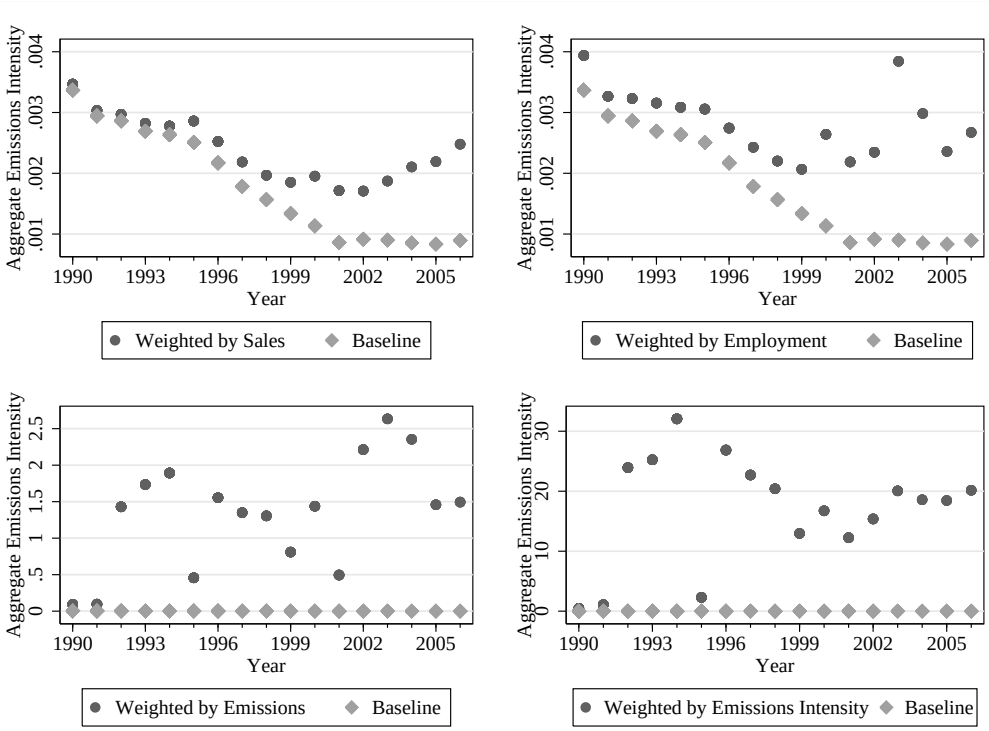


Figure A.9: Change in Aggregate Emissions Intensity - Comparison of Weights

Note: The panels in this figure present the evolution of aggregate emissions intensity over time. The "Baseline" aggregate emissions intensity is the same in each figure and is described in the text and in figure (A.6). Aggregate emissions intensity in each figure is calculated according to equation (1.2), the only difference being the choice of establishment weights. In the first panel, in the first row, the weight used is nominal sales from the NETS database. In the second panel, the weight is employment from the NETS database. In the first panel of the second row, the weight used is total emissions ("ModeledPounds") taken from the EPA's RSEI database, and the weight used in the final panel is emissions-intensity, calculated as the ratio of establishment emissions to real output.

Appendix B

Chapter 2 Empirical Decomposition

Empirical Decomposition

The following analysis provides additional motivation for the development of a combined theoretical framework that incorporates both within- and across-sector sources of variation. The approach builds on similar work in LaPlue (2016a), but with a different dataset that allows for a broader cross-sector analysis, more consistent with the highly distinct two-sector framework developed in this paper.

A. Specification and Setup

The following empirical work presents evidence of the relative importance of the across-sector composition and the within-sector aggregate technique channels identified in equation (2.32). To conduct this analysis, I make use of a method suggested by Mundlak et al. (2012), using fixed effects to determine the relative importance of cross-sector and within-sector variation in emissions, and then examine how those channels evolve over time.

Regressing time and sector fixed effects (a_t and a_s, respectively) on a panel of individual establishment specific emissions data, E_{nst}, allows me to decompose the total sum of squares into two orthogonal components, variation within sector (w_{st}) and variation across sector (a_s), in each period:

$$Emissions_{nst} = w_{st} + a_s + a_t$$

Thus, the within-sector variation (the Technique effect) is the residual effect remaining after accounting for cross-sector variation (the Composition effect) in the emissions variable. The cross-sector and within-sector variation are then expressed as a share by dividing by the total sum of squares in each year, and plotted over time.

B. Data and Results

To analyze the relative share of variation in emissions over time that is due to the across-sector channel and the within-sector channel, I require establishment-level emissions and their corresponding parent industry categorization. The US Environmental Protection Agency's (EPA) publicly available National Emissions Inventory (NEI) database contains establishment-level emissions along with include minimal establishment-specific information including geographic location, and the establishment's sector, given by either four-digit Standard Industrial Classification (SIC4) or six-digit North American Industrial Classification System (NAICS) code. The NEI has published data for the years 1990, 1996-2002, 2005. It contains establishment-level measures of several criteria pollutants[1] regulated under the Clean Air Act (CAA), and has been used in several related studies.[2]

In defining sectors, I follow the US Census in creating eight more-aggregated parent "groups" (e.g. Agriculture, Mining, Construction, Manufacturing, Services, etc.) based on each establishment's two-digit SIC or NAICS code. This generates eight, rather than the two sectors laid out in the preceding combined framework, but is quite similar in spirit to the theoretical framework. It is noteworthy that there was a substantial shift in industry classification approaches in 2002 (from SIC to NAICS). Because the EPA has not maintained the SIC industry codes alongside the updated NAICS codes in the NEI database, panel analysis that spans 2002 is generally very challenging with the NEI data. However, at the two-digit level, the industry mappings from SIC to NAICS are generally straightforward which facilitates aggregate panel analysis by "groups" across the 2002 transition year. Table (B.1) presents the list of industry groups and the corresponding SIC and NAICS codes comprising each group. [3] The results presented in Figure (B.1) are an average of the within- and across-sector variation for the criteria pollutants available all 11 years.[4] The results for each individual pollutant are available upon request. Figure (B.1) conveys a couple of distinct points. First, using this aggregate sector definition, the majority of observed changed in aggregate emissions are driven by variation within sectors, but the across-sector

[1]Including SO2, CO, NOX, NH3, Volatile Organic Compounds (VOCs), and Particulate Matter (PM10 and PM25)

[2]See Cui et al. (2015); Shapiro and Walker (2015); Levinson (2009) for recent examples of papers using this same data.

[3]The only two-digit NAICS code that does not map cleanly back to a single two-digit SIC code is 55 (Management Services), but it only comprises 32 of the 386,343 total observations (less than 0.01 percent). Omitting these observations does not change the results at the presented level of aggregation.

[4]CO, SO2, VOC, and NOX are available for all 11 years. Particulate matter and NH3 are only available for 6 and 10 of the years, respectively.

Table B.1: NEI Industry Groups

Group	Description	SIC2 Code(s)	NAICS2 Code(s)	Observations
1	Agriculture, Forestry, Fishing and Hunting	01-02	11	12,098
2	Mining	10-14	21	92,250
3	Construction	15-17	23	4,065
4	Manufacturing	20-39	31-33	304,626
5	Transportation, Warehousing, Pub. Utilities	40-49	22, 48-49	119,886
6	Wholesale and Retail Trade	50-59	42-47, 72	75,273
7	Services	70-89	51, 54-81*	112,374
8	Public Administration	90-98	92	12,747

Group definitions are taken from the US Census.
*With the introduction of NAICS, a new category, "Management Services" was created, NAICS2 code 55, from numerous different SIC2 categories, thus making matching challenging, even at this aggregated level. However, this group only represents 32 of the 386,343 observations, and thus my inability to accurately group each of them is unlikely to introduce significant issues in the analysis. Dropping those 33 observations from the sample does not change the results.

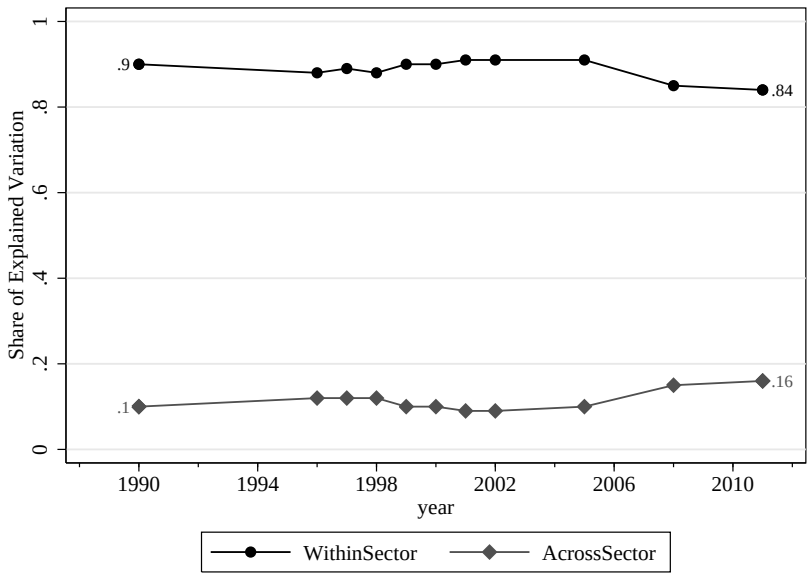


Figure B.1: Variation in Emissions Within and Across Sector Groups (NEI, SO2)
Note: The SO2 data are taken from establishment-level data released in the EPA's NEI database. The top line plots the relative share of changes in this measure of emissions that is explained by variation within sector groups. The lower line plots the relative share of changes in emissions explained by variation within sector groups. Group definitions are provided in table (B.1).

variation is not trivial, ranging up to 16 percent in 2011. Second, the degree of within-sector dominance is changing–the share of total variation explained by cross-sector composition differences increased by roughly 60 percent between 1990 and 2011. These results provide strong evidence that both within- and across-sector variation are important channels driving observed emissions outcomes.

Appendix C

Chapter 2 Theory

Average Productivity and Aggregation in the Closed Economy

The distribution of firms operating in a sector can then be characterized by an ex-post distribution of productivity levels, which is bounded by the sector's cut-off productivity level, φ_s^*.

$$\mu_s(\varphi) = \begin{cases} \frac{g(\varphi)}{1-G(\varphi_s^*)} & \varphi \geq \varphi_s^* \\ 0 & \text{otherwise} \end{cases} \tag{C.1}$$

where $g(\varphi)$ is the density function of φ . The probability of drawing a productivity level above φ_s^* and remaining in the market is $[1 - G(\varphi_s^*)]$. Thus the probability distribution $\mu_s(\varphi)$ represents the conditional probability of successful entry.

Just as in Bernard et al. (2007b), $\tilde{\varphi}_s$ is an output weighted productivity average across all firms operating in the market:[1]

$$\tilde{\varphi}_s(\varphi_s^*) \equiv \left[\int_{\varphi_s^*}^{\infty} \varphi^{(\sigma-1)} \mu_s(\varphi) \mathrm{d}\varphi \right]^{\frac{1}{(\sigma-1)}} \tag{C.2}$$

This can be used to rewrite the aggregate price index and output level for a given sector from (2.2) and (2.3) as

$$P_s = \left[\frac{1}{1-G(\varphi_s^*)} \int_{\varphi_s^*}^{\infty} p(\varphi)^{(1-\sigma)} M_s g(\varphi) \mathrm{d}\varphi \right]^{\frac{1}{1-\sigma}} = M_s^{\frac{1}{1-\sigma}} p(\tilde{\varphi}_s) \tag{C.3}$$

$$Q_s = M_s^{1/\rho} \eta_s R P_s^{\sigma-1} \left(p(\tilde{\varphi}_s)\right)^{-\sigma} = M_s^{1/\rho} q_s(\tilde{\varphi}_s) \tag{C.4}$$

[1] Using the fact that, from (2.3) , $\frac{q(\varphi_1)}{q(\tilde{\varphi}_1)} = \left(\frac{\varphi_1}{\tilde{\varphi}_1}\right)^{\sigma}$, $\tilde{\varphi}_s$ can be written as $\tilde{\varphi}_s^{-1} = \left[\int_{\varphi_s^*}^{\infty} \varphi^{-1} \left(\frac{q(\varphi_s)}{q(\tilde{\varphi}_s)}\right) g(\varphi) \mathrm{d}\varphi\right]$

Propositions

Proof of Proposition 1 –

The integrated free trade equilibrium is referenced by a vector of ten variables:

$[\varphi_1^*, \varphi_2^*, P_1, P_2, R, p_1(\varphi), p_2(\varphi), w, i, t_1]$, where, the simplifying assumption that only sector one pollutes implies that $\alpha_2 = 0$ and also $t_2 = 0$.

Choose labor as the numeraire good, so $w = 1$. From the free-entry condition (D.3), V_s is monotonically decreasing in φ_s^*. Thus (D.3) defines a unique equilibrium value of φ_s^*, as a function of model parameters and fixed variables.

From (C.2), φ_s^* uniquely determines $\tilde{\varphi}_s(\varphi_s^*)$. Combining the fact that $r_s(\tilde{\varphi}_s) = \left(\frac{\tilde{\varphi}_s}{\varphi_s^*}\right)^{(\sigma-1)} r(\varphi_s^*)$ with the zero profit cut-off condition (2.11), average revenues and profits (denoted by a "bar") can be expressed as functions of φ_s^* and factor rewards:

$$\begin{aligned} \bar{r}_s &= \left(\frac{\tilde{\varphi}_s(\varphi_s^*)}{\varphi_s^*}\right)^{\sigma-1} \sigma \cdot f_s \frac{w^{1-\beta_s} i^{\beta_s} \nu_s}{(1-\alpha_s)(1-\theta_s)} \\ \bar{r}_s &= \left(\frac{\tilde{\varphi}_s(\varphi_s^*)}{\varphi_s^*}\right)^{\sigma-1} \sigma \cdot f_s \zeta_s \left(w^{1-\beta_s} i^{\beta_s} \nu_s\right)^{1-\alpha_s} t_s^{\alpha_s} \end{aligned} \tag{C.5}$$

where $(1-\theta_s) = \left(\frac{w^{1-\beta_s} i^{\beta_s} \nu_s}{t_s} \frac{\alpha_s}{1-\alpha_s}\right)^{\alpha_s}$, and $\zeta_s = \alpha_s^{-\alpha_s}(1-\alpha_s)^{(\alpha_s-1)}$ is comprised of technology parameters from the assumed Cobb-Douglas production structure. Average profits are then given by

$$\bar{\pi}_s = \left[\left(\frac{\tilde{\varphi}_s(\varphi_s^*)}{\varphi_s^*}\right)^{\sigma-1} - 1\right] \cdot f_s \zeta_s \left(w^{1-\beta_s} i^{\beta_s} \nu_s\right)^{1-\alpha_s} t^{\alpha_s}$$

In each sector, total payments for factors of production (denoted with the p superscript) equals total revenue minus profits:

$$w L_s^p + i K_s^p + t_s Z_s^p = R_s - \Pi_s$$

and combining free entry (D.3) with steady-state stability, $[1 - G(\varphi_s^*)] \cdot M_{es} = \delta \cdot M_s$, the total value of payments used for entry in a sector is equal to total sector profits:

$$\Pi_s = M_s \bar{\pi}_s = M_{es} f_{es} \zeta_s \left(w^{1-\beta_s} i^{\beta_s} \nu_s\right)^{1-\alpha_s} t^{\alpha_s} = w_s L_s^e + i_s K_s^e + t_s Z_s^e \tag{C.6}$$

thus, using the market clearing conditions in (2.16), the sum of total payments to factors in each sector equals total revenue, recalling that sector one is the polluting sector and thus

$Z_2 = 0$

$$\begin{aligned} wL_1 + iK_1 + t_1 Z_1 &= R_1 \\ wL_2 + iK_2 &= R_2 \end{aligned} \tag{C.7}$$

Since this is true for both sectors, aggregate revenue equals aggregate income (where the "bar" on a factor denotes it's fixed endowment level):

$$w\bar{L} + i\bar{K} + t_1 Z_1 = R$$

Equilibrium factor demands follow from the Cobb-Douglas production function and the marginal products of each factor (note: all firms in a given sector have similar production structure and factor intensities), and thus total payments to factors are a constant share of sector revenues:

$$L_s = \frac{(1-\alpha_s)(1-\beta_s)R_s}{w}, \qquad K_s = \frac{(1-\alpha_s)\beta_s R_s}{i}, \qquad Z_1 = \frac{\alpha_1 R_1}{t_1} \tag{C.8}$$

Combining these demands with the factor market clearing conditions for labor and capital (recalling that the emissions tax is exogenously set), and using the fact that consumers allocate a constant share of income $\{\eta, (1-\eta)\}$ across each sector, I obtain the integrated equilibrium capital and labor allocations as a function of parameters and the exogenous endowments:

$$K_1 = \left(\frac{\beta_1\eta}{\beta_1\eta + \beta_2(1-\eta)}\right)\bar{K}, \quad K_2 = \left(\frac{\beta_2(1-\eta)}{\beta_1\eta + \beta_2(1-\eta)}\right)\bar{K} \tag{C.9}$$

$$L_1 = \left(\frac{(1-\beta_1)\eta}{(1-\beta_1)\eta + (1-\beta_2)(1-\eta)}\right)\bar{L}, \quad L_2 = \left(\frac{(1-\beta_2)(1-\eta)}{(1-\beta_1)\eta + (1-\beta_2)(1-\eta)}\right)\bar{L} \tag{C.10}$$

Now, solve (C.8) for the interest rate i, plugging-in L_1 and K_1 (from (C.9) and (C.10)). Factor returns in the integrated or autarky equilibrium are thus:

$$w = 1, \quad t_1 = \text{exogenously set}, \quad i = \frac{\bar{L}}{\bar{K}} \cdot \frac{\beta_1\eta + \beta_2(1-\eta)}{(1-\beta_1)\eta + (1-\beta_2)(1-\eta)} \tag{C.11}$$

With factor prices determined, prices follow from the pricing rule (2.9). Price indices follow from the fact that $P_s = M_s^{1/(1-\sigma)} p_s(\tilde{\varphi}_s)$ where $M_s = R_s/\bar{r}_s$. Using (C.8), total sector revenue can be written as: $R_s = \frac{L_s + iK_s}{1-\alpha_s}$, and average sector revenue is given by (C.5). Thus,

the mass of firms is solved as a function of factor prices, endowments, and the productivity cut-off and independent of the aggregate emissions level. Emissions demand can then be solved as a function of equilibrium values:

$$Z_1 = \frac{\alpha_1 R_1}{t_1} = Z_1(w,\, i,\, t_1,\, \bar{K},\, \bar{L},\, \varphi_1^*) \tag{C.12}$$

Given the recursive nature of the system, similar to Copeland and Taylor (2003), the level of emissions is changed through shocks to factor endowments, the emissions tax, or available abatement technology, or endogenous changes to factor prices or productivity.

Thus I have demonstrated the existence of an integrated equilibrium, characterized by the vector $\{\varphi_1^*,\, \varphi_2^*,\, P_1,\, P_2,\, R,\, p_1(\varphi),\, p_2(\varphi),\, w,\, i,\, t\}$.

This concludes the proof.

Factor Price Equalization Equilibrium –

The following discussion and result are used in several of the following propositions and are taken largely from a NBER working version of Bernard et al. (2007b) and are recreated here for convenience. I reintroduce country notation for this discussion.

Factor price equalization (FPE) is a theoretical result from the Heckscher-Ohlin framework that essentially shows that free-trade in goods can replicate free-movement of factors. In other words, countries have the option to trade their output or inputs, and either option chosen will result in the same equilibrium factor returns. The basic logic being that, contrary to the closed economy case, if a country has a relatively larger endowment of capital than labor, they can trade goods that are capital intense and thus increase the relative demand for capital above what it would be absent the ability to trade. This ability to trade in goods will lead factor prices to equalize across countries under a regime of free trade. Essentially, the factors can be traded explicitly, or implicitly via factor content in the traded goods. This result also relies on the absence of factor intensity reversals, i.e. sectors must use similar input ratios across countries.

FPE and my choice of labor as the numeraire implies that $w^F = w^H = w = 1$ while $i^F = i^H = i$. Because emissions taxes are assumed to be set according to a non-market based political process, FPE does not apply to emissions taxes except by chance.

Cost minimization implies the same relative capital to labor factor intensities will be used across countries and thus from (C.8)

$$\frac{L_s^F}{K_s^F} = \frac{L_s^H}{K_s^H} = \frac{i \cdot (1-\beta_s)}{w \cdot \beta_s} = \frac{i \cdot (1-\beta_s)}{\beta_s} \tag{C.13}$$

The factor market clearing conditions applied to capital and labor can be expressed as ratios which are only functions of the endogenous factor returns, model parameters and country endowments.

$$\frac{\bar{K^n}}{\bar{L^n}} = \lambda^n_{L_1}\left(\frac{K^n_1}{L^n_1}\right) + (1-\lambda^n_{L_1})\left(\frac{K^n_2}{L^n_2}\right), \qquad \lambda^n_{L_s} = \frac{L^n_s}{\bar{L^n}}$$

$$\frac{\bar{L^n}}{\bar{K^n}} = \lambda^n_{K_1}\left(\frac{L^n_1}{K^n_1}\right) + (1-\lambda^n_{K_1})\left(\frac{L^n_2}{K^n_2}\right), \qquad \lambda^n_{K_s} = \frac{K^n_s}{\bar{K^n}}$$

where $n \in \{H, F\}$, and bars denote the country's endowment.

Substituting in (C.13), these equations can now be rearranged to find each country's free trade equilibrium allocations of labor and capital (and, by extension, emissions):

$$\frac{\bar{K^n}}{\bar{L^n}} = \left(\frac{L^n_1}{\bar{L^n}}\right)\left(\frac{\beta_1}{i\cdot(1-\beta_1)}\right) + \left(\frac{\bar{L^n}-L^n_1}{\bar{L^n}}\right)\left(\frac{\beta_2}{i\cdot(1-\beta_2)}\right) \tag{C.14}$$

$$\frac{\bar{K^n}}{\bar{L^n}} = \left(\frac{\bar{L^n}-L^n_2}{\bar{L^n}}\right)\left(\frac{\beta_1}{i\cdot(1-\beta_1)}\right) + \left(\frac{L^n_2}{\bar{L^n}}\right)\left(\frac{\beta_2}{i\cdot(1-\beta_2)}\right) \tag{C.15}$$

$$\frac{\bar{L^n}}{\bar{K^n}} = \left(\frac{K^n_1}{\bar{K^n}}\right)\left(\frac{i\cdot(1-\beta_1)}{\beta_1}\right) + \left(\frac{\bar{K^n}-K^n_1}{\bar{K^n}}\right)\left(\frac{i\cdot(1-\beta_2)}{\beta_2}\right) \tag{C.16}$$

$$\frac{\bar{L^n}}{\bar{K^n}} = \left(\frac{\bar{K^n}-K^n_2}{\bar{K^n}}\right)\left(\frac{i\cdot(1-\beta_1)}{\beta_1}\right) + \left(\frac{K^n_2}{\bar{K^n}}\right)\left(\frac{i\cdot(1-\beta_2)}{\beta_2}\right) \tag{C.17}$$

and solving (C.14) - (C.17) for L^n_1, L^n_2, K^n_1, K^n_2 in each country yields the following equilibrium factor allocations for capital and labor[2]

$$L^n_1 = \frac{i\bar{K^n} - \left(\frac{\beta_2}{1-\beta_2}\right)\bar{L^n}}{\left(\frac{\beta_1}{1-\beta_1}\right) - \left(\frac{\beta_2}{1-\beta_2}\right)}, \qquad L^k_2 = \frac{\left(\frac{\beta_1}{1-\beta_1}\right)\bar{L^n} - i\bar{K^n}}{\left(\frac{\beta_1}{1-\beta_1}\right) - \left(\frac{\beta_2}{1-\beta_2}\right)} \tag{C.18}$$

[2]Using these factor allocation, one can most easily see that the Rybczynski theorem holds under these circumstances. Holding factor prices fixed, a rise in the country's capital endowment will raise output in sector one (the polluting sector) and lower it in the clean sector.

$$K_1^n = \frac{\left(\frac{\beta_1}{1-\beta_1}\right)\bar{K^n} - \left(\frac{\beta_1}{1-\beta_1}\right)\left(\frac{\beta_2}{1-\beta_2}\right)\frac{1}{i}\bar{L^n}}{\left(\frac{\beta_1}{1-\beta_1}\right) - \left(\frac{\beta_2}{1-\beta_2}\right)}, \qquad K_2^n = \frac{\left(\frac{\beta_1}{1-\beta_1}\right)\left(\frac{\beta_2}{1-\beta_2}\right)\frac{1}{i}\bar{L^n} - \left(\frac{\beta_2}{1-\beta_2}\right)\bar{K^n}}{\left(\frac{\beta_1}{1-\beta_1}\right) - \left(\frac{\beta_2}{1-\beta_2}\right)} \tag{C.19}$$

Now, recalling that labor is the numeraire good, aggregate income in each country equals aggregate revenue:

$$R^n = \bar{L^n} + i\bar{K^n} + t_1^n Z_1^n$$

In both countries, total sector payments to capital are a constant share, $(1-\alpha_s)\beta_s$, of sector revenues which are a constant share of total world expenditures, η_s. Plugging in the free-trade allocations of capital and labor into the relative wage given in (C.13) yields the equilibrium free-trade factor return:

$$i = \frac{(\bar{L^H} + \bar{L^F})}{(\bar{K^H} + \bar{K^F})} \cdot \frac{\beta_1\eta + \beta_2(1-\eta)}{(1-\beta_1)\eta + (1-\beta_2)(1-\eta)} \tag{C.20}$$

which is identical to the result given in the integrated economy, (C.11), recognizing that in the integrated economy, the total stocks of labor and capital are merely the sum of the stock of each input in each country, $\bar{L^H} + \bar{L^F} = \bar{L}$ and $\bar{K^H} + \bar{K^F} = \bar{K}$.

The FPE set requires the standard assumption that the countries' factor endowment ratios lie between equilibrium integrated factor intensities, or what is sometimes called their "cone of diversification." If this does not hold, only one good would be produced and factor returns would mirror a single good case in which they become functions of their marginal products and respective country endowments.

Proof of proposition 2 –

The zero profit productivity cut-off is determined by (D.3) as a function of fixed variables and parameters. In the move from autarky to free trade this remains unchanged, and thus the productivity cut-off, φ_s^*, is unchanged. Average productivity is determined by (C.2) and when the productivity cut-off does not change, average productivity remains unchanged as well.

(a) Emissions demand is given by (2.21). When there is no change in the productivity cut-off or relative stringency of environmental policy, average output, given by $q(\tilde{\varphi}_s) = \left(\frac{\tilde{\varphi}_s}{\varphi_s^*}\right)^\sigma q_s^* = \left(\frac{\tilde{\varphi}_s}{\varphi_s^*}\right)^\sigma (\sigma-1)f_s\varphi_s^*$, and firms' abatement investment, θ_1, remain unchanged, and the emissions demand is governed by changes working through the mass of firms and varieties. For the polluting sector this is given by $M_1 = \frac{R_1}{\bar{r}_1}$ and, using (C.5), (C.7) and

(C.8), can be re-written as

$$M_1 = \frac{wL_1 + iK_1}{(1-\alpha_1)\left(\left(\frac{\tilde{\varphi}_1}{\varphi_1^*}\right)^{\sigma-1}\sigma f_1\left(\frac{w^{\beta_1} i^{1-\beta_1}\nu_1}{(1-\theta_1)(1-\alpha_1}\right)\right)}$$

Recalling that labor is the numeraire, and using (2.8), and the equilibrium capital and labor allocations given in (C.18) and (C.19) this can be written as

$$M_1 = \frac{i^{1-\beta_1}\bar{K} - \frac{1}{i^{\beta_1}}\bar{L}\frac{\beta_2}{1-\beta_2}}{\left(\frac{1-\beta_1}{\beta_1}\right)^{\beta_1}\left(\frac{\beta_1}{1-\beta_1} - \frac{\beta_2}{1-\beta_2}\right)} \cdot \frac{(1-\theta_1)}{\left(\frac{\tilde{\varphi}_1}{\varphi_1^*}\right)^{\sigma-1}\sigma f_1} \tag{C.21}$$

If the home country enjoys a relative abundance of capital, compared to the foreign nation, and thus a comparative advantage in relatively dirty production, under autarky the relative price of capital is lower in the home country, as can be seen in (C.11). Using the price index given in (2.12), a lower relative price for capital implies a lower relative output price under autarky for goods in sector one. As long as this is not reversed by a significantly higher emissions tax, the home country enjoys a comparative advantage in capital intense, dirty production. In the move from autarky to free trade, relative prices converge and thus the relative return to labor in the home country rises, and falls in the foreign country. Thus, in the move from autarky to free trade, the mass of firms rises in sector one when the home country holds a comparative advantage in dirty production, and falls if the country holds a comparative advantage in clean production.

(b) If the home country has a relative abundance of capital and resources would flow into the polluting sector, thereby raising emissions demand, this will only be reversed if increased environmental regulations raise up the cost of emissions relative to the cost of the capital-labor bundle, via a rise in the emissions tax, t_1, thereby inducing firms to increase their investment in abatement, θ_1.

(c) Comparative statics of (C.21) with respect to the relative wage, reveals that the comparative advantage effect, working through change in relative prices and thus changes in the mass of firms, is decreasing in θ_1 and the fixed cost, f_1, ceteris paribus.

This concludes the proof.

Proof of proposition 3 –

Continue to hold home-country labor as the numeraire good, and thus $w^H = 1$.

Suppose that the factor price vector $\{1, i^H, t^H, w^F, i^F, t^F\}$ is known. Labor and capital endowments continue to be fixed in each country and the share allocated to each sector

must account for entry as well as export and domestic production: $L_s^n = L_s^{ne} + L_s^{np} + L_s^{nx}$ and $K_s^n = K_s^{ne} + K_s^{np} + K_s^{nx}$ for $s \in \{1,2\}$ and $n \in \{H,F\}$. The allocation of factor endowments of capital and labor are allocated as in (C.18) and (C.19) with slight adjustment to accommodate costly trade and different factor prices across countries. As in the proof of *Proposition 1*, payments for capital and labor inputs plus emissions taxes paid for emissions (when firms release emissions) will equal total sector revenue in each sector and each country: $\{R_s^n\}$ for $s \in \{1,2\}$ and $n \in \{H,F\}$. In the costly trade equilibrium, total sector revenue is given by the market clearing condition (2.31) which combines with the sector revenue equations: $R_1^n = \frac{w^n \cdot L_1^n + i^n \cdot K_1^n}{1-\alpha_1}$ and $R_2^n = w^n \cdot L_2^n + i^n \cdot K_2^n$. Thus total country revenues: $\{R^H, R^F\}$ are pinned down.

The pricing rule (2.23) determines variety prices as a function of factor returns, the emissions tax, and trade costs and productivity: $\{p_{sd}^n(\tilde{\varphi}_{sd}^n), p_{sx}^n(\tilde{\varphi}_{sx}^n)\}$ for $s \in \{1,2\}$ and $n \in \{H,F\}$.

With wages, prices, and total revenues identified, the productivity cut-offs, $\{\varphi_s^{n*}, \varphi_{sx}^{n*}\}$ and sector price indices, $\{P_1^n, P_2^n\}$, for $s \in \{1,2\}$ and $n \in \{H,F\}$ are the solution to a system of six equations for each sector given by (2.26), (2.29) and (2.23), where the mass of firms is given by $M_s^n = R_s^n / \bar{r}_s^n$, probability of exporting is given by $\chi_s^n = \frac{1-G(\varphi_{sx}^{*n})}{1-G(\varphi_s^{*n})}$, average revenue is given by $\bar{r}_s^n = \left[\left(\frac{\tilde{\varphi}_s^n(\varphi_s^{*n})}{\varphi_s^{*n}}\right)^{\sigma-1} f_s + \chi_s^n \left(\frac{\tilde{\varphi}_{sx}^n(\varphi_{sx}^{*n})}{\varphi_{sx}^{*n}}\right)^{\sigma-1} f_{sx}\right] \sigma \frac{(w^n)^{1-\beta_s}(t^n)^{\beta_s}\nu_s}{(1-\theta_s^n)(1-\alpha_1)}$, and $(1-\theta_s^n) = \left(\frac{(w^n)^{1-\beta_s}(t^n)^{\beta_s}\nu_s}{t_s^n} \frac{\alpha_1}{1-\alpha_1}\right)^{\alpha_1}$. Thus, the system of equations solves for the six unknowns in each sector, given the equilibrium wage vector, and the model parameters.

In the costly trade equilibrium, total sector revenue is given by the market clearing condition (2.31) which combine with the sector revenue equations to determine relative wages. Exogenous environmental regulations determine the emissions tax. Thus, total revenue, $R^n = R_1^n + R_2^n$, is solved for independently of the level of emissions, and all key model variables are solved except for the emissions level.

The key feature of the present framework regards the equilibrium level of emissions and the recursive nature of the model as in Copeland and Taylor (2003). Total sector revenue, the mass of firms, and national income can be solved independently of the emissions level to determine relative wages, and factor allocations. These equilibrium values can then be plugged into (C.12) to determine the equilibrium level of emissions demand.

This concludes the proof.

Proof of proposition 4 –

Emissions demands are given by (2.20). Recognizing that sector revenue is simply given by $R_s = Q_s \cdot P_s$, multiplying and dividing by the sector price index decomposes the sector

emissions demand into an output (similar to the traditional scale effect) and a technique channel:

$$Z_1 = \frac{R_1}{P_1} \times \frac{\alpha_1 P_1}{t_1} \tag{C.22}$$

Using the equilibrium results from *Proposition 2*, when there are no changes to relative wages or factor allocations–as would be the case if the country began trading with a partner having identical relative prices–R_1 remains unchanged. The value of entry under costly trade is equal to the value of entry in the closed economy (2.13) plus the value of exporting. From equations (2.26) and (2.29), the value of entry under costly trade is monotonically decreasing in φ_s^{n*} and thus the reduction in trade barriers raises the productivity cut-off, φ_s^{n*}. Average productivity, given by (C.2) is monotonically increasing in φ_s^{n*}, and thus rises as well. This, combined with increasing foreign imports, serves to reduce prices, and the price index, in the sector, reducing emissions demand via the technique effect. However, as can be seen in (C.22), these two effects–rising real output driving emissions up through a scale effect, and falling prices reducing emissions demand via the technique effect–will exactly offset. Thus, absent additional changes to relative wages and cross-sector resource allocations, the endogenous productivity gains from trade leave total emissions unchanged.

This concludes the proof.

Proof of proposition 5 –

From *Proposition 4,* a reduction in trade barriers under costly trade raises the productivity cut-off, φ_s^*, in both sectors.

(a) Price indices under costly trade are given by (2.30), while prices under autarky are given by

$$P_s^H = \left[M_s p(\tilde{\varphi}_s)^{1-\sigma}\right]^{1/(1-\sigma)} \tag{C.23}$$

Since prices are monotonically declining in productivity, the rise in average weighted productivity in both the home country and the trading partner following the opening of trade serves to reduce prices and raise real output in both sectors, thus raising emissions demand via the scale effect.

(b) Using (2.33), emissions demand, given in (2.32) can be written equivalently as

$$Z_1^n = Q^n \times \frac{1}{\frac{1}{\psi_1^n} + \left(\frac{M_2^n}{M_1^n}\right)^{1/\rho} \cdot \frac{q_2(\tilde{\varphi}_2^n)}{q_1(\tilde{\varphi}_1^n)} \cdot \frac{1}{\psi_2^n}} \times \frac{(1-\theta_1^n)^{(1-\alpha_1)/\alpha_1}}{(M_1^n)^{1/(\sigma-1)} \tilde{\varphi}_1^n \rho} \tag{C.24}$$

To evaluate the composition effect under costly trade, first, consider relative average output.

In the combined framework, the free entry condition under autarky, in either country, is given by (2.13). Using (2.10), where $\bar{\pi}_s = \pi(\tilde{\varphi}_s)$ and $\bar{r}_s = \bar{q}_s\bar{p}_s$, the free-entry condition can be re-written as

$$\frac{[1 - G(\varphi_s^{*Aut})]}{\delta}\left(\frac{\bar{q}_s^{Aut}}{(\sigma-1)\tilde{\varphi}_s^{Aut}} - f_s\right) = f_{es} \tag{C.25}$$

where Aut denotes values under autarky.

Under costly trade the free-entry condition is given by (2.29) and firms can earn profits from domestic sales and exports. As discussed above, the free-entry cut-off, $\varphi^*{}_s$, rises under costly trade and the free-entry condition under costly trade can be re-written as

$$\frac{[1 - G(\varphi_s^{*CT})]}{\delta}\left[\left(\frac{\bar{q}_s^{CT}}{(\sigma-1)\tilde{\varphi}_s^{CT}} - f_s\right) + \chi_s^{CT}\left(\frac{\tau_s\bar{q}_{sx}^{CT}}{(\sigma-1)\tilde{\varphi}_{sx}^{CT}} - f_{sx}\right)\right] = f_{es} \tag{C.26}$$

where CT denotes values under costly trade.

Comparing this expression with the condition under autarky, $\varphi_s^{*Aut} < \varphi_s^{*CT}$ and $\tilde{\varphi}_s^{Aut} < \tilde{\varphi}_s^{CT}$. In addition, $f_s < f_s + f_{sx}$. Thus, to maintain the equality is must be the case that average output under costly trade, accounting for output "melting away" due to trade costs, is greater than average output under autarky: $\bar{q}_s^{CT} + \chi_s\tau_s\bar{q}_{sx}^{CT} > \bar{q}_s^{Aut}$.

Second, consider the relative change in productivity in the two sectors.

Under autarky, relative price indices are given by

$$\frac{P_1^n}{P_2^n} = \left(\frac{M_1^n}{M_2^n}\right)^{\frac{1}{1-\sigma}}\frac{p_1(\tilde{\varphi}_1)}{p_2(\tilde{\varphi}_2)} \tag{C.27}$$

where $n \in \{H, F\}$ denotes the country. The relative price index can be simplified, using the pricing rule (2.9) as

$$\frac{P_1^n}{P_2^n} = \left(\frac{\eta}{1-\eta}\cdot\frac{f_2}{f_1}\right)^{\frac{1}{1-\sigma}}\frac{\varphi_2^{n*}}{\varphi_1^{n*}}\left[\frac{1}{(1-\theta_1^n)}\left(\frac{i^n}{w^n}\right)^{\beta_1-\beta_2}\right]^{1/\rho} = \tag{C.28}$$

where $\beta_1 > \beta_2$ and $(1-\theta_s) = \left(\frac{w^{1-\beta_s}i^{\beta_s}\nu_s}{t_s}\frac{\alpha_s}{1-\alpha_s}\right)^{\alpha_s}$. Thus, assuming $\beta_1(1-\alpha_1) > \beta_2$, the larger relative endowment of capital in the home country, implies that the relative price index, P_1^n/P_2^n, is lower in the home country than in the foreign under autarky.

Under costly trade relative prices are given by

$$\frac{P_1^n}{P_2^n} = \left[\frac{M_1^n\left(p_{1d}^n(\tilde{\varphi}_1^n)\right)^{(1-\sigma)} + \chi_1^j M_1^j\left(\tau_1 p_{1d}^j\tilde{\varphi}_1^j\right)\right)^{(1-\sigma)}}{M_2^n\left(p_{2d}^n(\tilde{\varphi}_2^n)\right)^{(1-\sigma)} + \chi_2^j M_2^j\left(\tau_2 p_{2d}^j\tilde{\varphi}_2^j\right)\right)^{(1-\sigma)}}\right]^{1/(1-\sigma)} \qquad \text{for } j \neq n \tag{C.29}$$

and relative prices converge to their autarky values as $\tau_s \to \infty$ and as $f_{sx} \to \infty$. Under free trade, $P_1^H = P_1^F$ and $P_2^H = P_2^F$. As $\tau_s \to 1$ and as $f_{sx} \to 0$, prices converge to their free-trade values and thus $\frac{P_1^n}{P_2^n}$ rises in the home country and falls in the foreign.

Barring cross-sector differences in fixed or trade costs, from (2.26) this implies that Λ_s^n is smaller in the country's comparative advantage sector, and thus the export cut-off is closer to the entry cut-off in the comparative advantage sector. Since the value of entry (2.29) is monotonically decreasing in φ_s^* and a smaller Λ_s^n implies a greater increase in the value of entry, the productivity cut-off will rise by more in the comparative advantage sector.

This in turn implies that, in the home country, relative average output, $\frac{\bar{q}_1^n}{\bar{q}_2^n}$, rises following a reduction in trade barriers.

Finally, the trade or competitiveness term, $1/\psi_s^n$, also rises following a reduction in trade barriers. Using the definition, $\psi_s^H \equiv \left[1 + \frac{\chi_s^F M_s^F \tau_s^{1-\sigma} \cdot \left(p_s^F(\tilde{\varphi}_{sx}^F)\right)^{1-\sigma}}{M_s^H (p_s^H(\tilde{\varphi}_s^H))^{1-\sigma}}\right]^{1/(1-\sigma)}$, the competitiveness term, ψ_s^H, rises towards 1 as $\tau_s \to \infty$, and falls when this trend is reversed. As trade costs fall, ψ_s^n falls as the second term in brackets rises from zero to some positive value, capturing the increased competitive pressure on prices due to the rise in foreign exporters.[3] Since imports rise faster (or by more) in the comparative disadvantaged sector, the trade terms falls by more in the comparative disadvantaged sector two. Thus, the trade induced changes in average output and increased demand due to competitive pressure on prices raises emissions demand if the country holds a comparative advantage in emissions intense production.

(c) The mass of firms is given by $M_s^n = R_s^n/\bar{r}_s^n$. Other things equal, the rise in average productivity and corresponding rise in average firm size lowers the mass of firms. Since the rise in productivity is greater in the comparative advantage sector, the fall in the mass of firms is also greater, which drives down the relative mass of firms in the home country, μ_1^H.

However, as shown in *Proposition 2*, in the move from autarky to free trade the relative mass of firms rises in accordance with a country's comparative advantage. The relative mass of firms is given by

[3]Under costly trade, the direct effect of a reduction in tariffs may not be to lower emissions if the home country has a significant comparative advantage in emissions intense production. In this case, the direct effect of increased foreign competition could be off-set by a rise in the mass of firms, M_1^H, producing in the emissions intense sector as resources moved out of sector two and into sector one, thus driving ψ_1^H higher. However, in this case, the effect would be dominated by the larger fall in the comparative-disadvantaged sector, and thus the total effect in (C.24) of changes in ψ_s^H will be to lower emissions.

$$\frac{M_1^n}{M_2^n} = \left(\frac{i^n\left(1-\beta_2\right) - \frac{\bar{L^n}}{\bar{K^n}}\left(\beta_2\right)}{\left(\beta_1\right)\frac{\bar{L^n}}{\bar{K^n}} - i^n\left(1-\beta_1\right)}\right) \frac{\left[\left(\frac{\tilde{\varphi}_2^n}{\varphi_2^{n*}}\right)^{\sigma-1} f_2 + \chi_2^n(\varphi_2^{n*}) \cdot \left(\frac{\tilde{\varphi}_{2x}^n}{\varphi_{2x}^{n*}}\right)^{\sigma-1} f_{2x}\right]}{\left[\left(\frac{\tilde{\varphi}_1^n}{\varphi_1^{n*}}\right)^{\sigma-1} f_1 + \chi_1^n(\varphi_1^{n*}) \cdot \left(\frac{\tilde{\varphi}_{1x}^n}{\varphi_{1x}^{n*}}\right)^{\sigma-1} f_{1x}\right]} \left(\frac{1}{i^n}\right)^{\beta_1-\beta_2} \cdot \frac{\nu_2}{\nu_1} \cdot (1-\theta_1^n) \tag{C.30}$$

In the move from autarky to free trade there is no change to the productivity cut-off. Thus, holding emissions intensity fixed at the firm level via environmental policy, the relative mass of firms adjusts according to the country's comparative advantage based on differences in relative endowments:[4]

$$\begin{aligned}
\frac{\partial(\mathrm{M_1^n}/\mathrm{M_2^n})}{\partial(i^n/w^n)} \quad = \quad & \underbrace{(i^n)^{\beta_2-\beta_1}\left(\left(1+\beta_2-\beta_1\right)\left(1-\beta_2\right) - \frac{\bar{L^n}}{\bar{K^n}}\frac{\left(\beta_2\right)\left(\beta_2-\beta_1\right)}{i^n}\right)}_{(+)} \\
& \times \underbrace{\left(\left(\beta_1\right)\frac{\bar{L^n}}{\bar{K^n}} - i^n\left(1-\beta_1\right)\right)^{-1}\left(1-\theta_1^n\right)}_{(+)} \\
& + \underbrace{(i)^{\beta_2-\beta_1}\left(i^n\left(1-\beta_2\right) - \frac{\bar{L^n}}{\bar{K^n}}\left(\beta_2\right)\right)}_{(+)} \\
& \times \underbrace{\left[\left(\left(\beta_1\right)\frac{\bar{L^n}}{\bar{K^n}} - i^n\left(1-\beta_1\right)\right)^{-2}\left(1-\beta_1\right)\left(1-\theta_1^n\right) + \left(\left(\beta_1\right)\frac{\bar{L^n}}{\bar{K^n}} - i^n\left(1-\beta_1\right)\right)^{-1}\frac{\beta_1}{i^n}(1-\theta_1^n)\right]}_{(+)}
\end{aligned}$$

Thus, the productivity gains dampen but do not reverse the cross-sector resource movement of the composition effect driving changes in the relative mass of firms.

(d) Emissions demand is given by

$$Z_1 = \frac{\alpha_1 R_1}{t_1} = Q_1 \cdot \frac{\alpha_1 P_1}{t_1} \tag{C.31}$$

where the technique effect is captured by $\frac{\alpha_1 P_1}{t_1}$. Under costly trade, prices indices are given by (2.30) and the absolute change in the price index following a trade liberalization is ambiguous, depending importantly on changes in relative factor endowments and prices between the trading partners, relative size of the two markets. However, as discussed in (a), above, variety prices are monotonically decreasing in productivity, and thus the rise in the productivity cut-off, for both the home country and the trading partner, ensures that prices are declining in productivity following a trade liberalization.

[4]Recalling that labor is the numeraire good, and $w = 1$ which implies $(1-\theta_1) = \left(\frac{w^{1-\beta_1} i^{\beta_1} \nu_1}{t_1}\frac{1-\alpha_1}{\alpha_1}\right)^{\alpha_1} = \left(\frac{i^{\beta_1}\nu_1}{t_1}\frac{1-\alpha_1}{\alpha_1}\right)^{\alpha_1}$

Appendix D

Chapter 3 Theory

Optimal Abatement Choice

A firm's emissions intensity is also simply the ratio of a firm's emissions to their output, and for those familiar with the properties of Cobb-Douglas production functions, a firm's cost minimizing choice of per-unit emissions will be determined by their choice of θ, as shown in (3.2): $e \equiv \frac{z}{q} = \frac{\alpha_s MargCost}{t_s}$, where, from cost minimization of (3.3), marginal costs are given by $\frac{(w^{1-\beta_s} i^{\beta_s} \nu_s)^{1-\alpha_s} \tau_s^{\alpha_s} \zeta_s}{\varphi}$.

Thus, a firm's emissions intensity can be written equivalently as:

$$\frac{(1-\theta_s)^{\frac{1-\alpha_s}{\alpha_s}}}{\varphi} = \frac{\alpha_s}{\tau_s} \frac{(w^{1-\beta_s} i^{\beta_s} \nu_s)^{1-\alpha_s} \tau_s^{\alpha_s} \zeta_s}{\varphi} \tag{D.1}$$

Solving for θ yields the firm's optimal abatement share decision:

$$1 - \theta_s = \left(\frac{w^{1-\beta_s} i^{\beta_s} \nu_s}{\tau_s} \frac{\alpha_s}{1-\alpha_s} \right)^{\alpha_s} \tag{D.2}$$

which concludes the result.

Free Entry Condition

The expected value of entry is given by the probability of successful entry, $1 - G(\varphi_s^*)$, times expected profits, which are weighted by an exogenous probability of exit or "death," δ.

summing profits across all incumbent firms and can be written as a function of the productivity cut-off, the productivity distribution from which the firms draw, $g(\varphi)$, a and fixed production and entry costs.[1]

[1] See Bernard et al. (2007b) and LaPlue (2016b) for further discussion of this condition.

$$V_s = \frac{[1 - G(\varphi_s^*)] \cdot \bar{\pi}_s}{\delta} = f_{es}(w^{1-\beta_s} i^{\beta_s} \nu_s)^{1-\alpha_s} \tau_s^{\alpha_s} \zeta_s \tag{D.3}$$

With average profits, given by $\bar{\pi}_s = \pi_s(\tilde{\varphi}_s) = \frac{r_s(\tilde{\varphi}_s)}{\sigma} - f_s(w^{1-\beta_s} i^{\beta_s} \nu_s)^{1-\alpha_s} \tau_s^{\alpha_s} \zeta_s$, the zero-profit condition given by, $r_s(\varphi_s^*) = \sigma f_s(w^{1-\beta_s} i^{\beta_s} \nu_s)^{1-\alpha_s} \tau_s^{\alpha_s} \zeta_s$, and the fact that relative revenue of two firms with different productivity can be written as $\frac{r(\varphi')}{r(\varphi'')} = \left(\frac{\varphi'}{\varphi''}\right)^{(\sigma-1)}$,[2] the free-entry condition can be re-written as a function of the productivity cut-off, the productivity distribution from which the firms draw, $g(\varphi)$, δ, and fixed production and entry costs:

$$V_s = \frac{f_s}{\delta} \int_{\varphi_s^*}^{\infty} \left[\left(\frac{\varphi}{\varphi_s^*} \right)^{(\sigma-1)} - 1 \right] g(\varphi) \mathrm{d}\varphi = f_{es} \tag{D.4}$$

Thus, the Free-Entry condition, combined with the Zero-Profit Cut-off condition, is monotonically decreasing in the productivity cut-off, and thus uniquely identifies this equilibrium value, φ_s^*, independent of factor prices and other endogenous variables.

Other Equilibrium Conditions: Mass of Firms, Average Emissions Intensity, Aggregate Emissions Intensity

The following analysis expands on the model provided in (3.6) to show how fixed costs and environmental stringency work to affect the mass of firms and, by extension, aggregate emissions intensity.

Similar to results obtained in Melitz (2003), the equilibrium mass of firms, taken from LaPlue (2016b), is given by

$$M_s = \frac{R_s}{r(\tilde{\varphi}_s)} = \frac{\eta_s R}{\left(\frac{\tilde{\varphi}_s}{\varphi_s^*}\right)^{\sigma-1} \sigma \cdot f_s \cdot (w^{1-\beta_s} i^{\beta_s} \nu_s)^{1-\alpha_s} \tau_s^{\alpha_s} \zeta_s} \tag{D.5}$$

where η_s is a Cobb-Douglas share of income that consumers spend in the sector and aggregate income is can be written as $R = \frac{wL + iK}{1-\alpha}$ where L and K represent fixed, national endowments. The variable $r(\tilde{\varphi}_s)$ represents average revenue in the sector (or, equivalently, revenue of the average firm), which can be rewritten using a zero-profit condition:

[2] From the CES demand setup, a firm's revenue is given by $R_s P_s^{\sigma-1} p_s(\varphi)^{1-\sigma}$ as in Melitz (2003); Bernard et al. (2007b)

$$\pi(\varphi) = \frac{r(\varphi)}{\sigma} - f_s(w^{1-\beta_s} i^{\beta_s} \nu_s)^{1-\alpha_s} \tau_s^{\alpha_s} \zeta_s \qquad \rightarrow \qquad r(\varphi_s^*) = \sigma \cdot f_s \cdot (w^{1-\beta_s} i^{\beta_s} \nu_s)^{1-\alpha_s} \tau_s^{\alpha_s} \zeta_s$$

and the relationship between two firms with different productivity levels: $\frac{r(\tilde{\varphi}_s)}{r(\varphi_s^*)} = \left(\frac{\tilde{\varphi}_s}{\varphi_s^*}\right)^{\sigma-1}$.

Average emissions intensity is obtained by multiplying and dividing AEI by the mass of firms, $EI_s = M_s \cdot e(\tilde{\varphi}_s)$ and $e(\tilde{\varphi}_s) = \frac{\alpha_s P_s}{M_s t_s}$. As in Bernard et al. (2007b); LaPlue (2016b), etc. the sector price index can be written as a function of average prices and the mass of firms: $P_s = M_s^{\frac{1}{1-\sigma}} p(\tilde{\varphi}_s)$, and an optimal firm-price is a markup, $\rho = \frac{\sigma-1}{\sigma}$, over the firm's marginal cost. Thus, the emissions intensity of the average firm can be written as

$$\begin{aligned} e(\tilde{\varphi}_s) &= \frac{\alpha_s p(\tilde{\varphi}_s)}{M_s^{\frac{1}{\rho}} \tau_s} \\ &= \frac{1}{M_s^{\frac{1}{\rho}} \rho \tilde{\varphi}_s} \left(\frac{w^{1-\beta_s} i^{\beta_s} \nu_s}{\tau_s} \frac{\alpha_s}{1-\alpha_s} \right)^{1-\alpha_s} \end{aligned} \tag{D.6}$$

As in Melitz (2003), average productivity, $\tilde{\varphi}_s$, is monotonically increasing in the productivity cut-off value, φ_s^*, that firms must exceed in order to profitably remain in the market:

$$\tilde{\varphi}_s(\varphi_s^*) \equiv \left[\int_{\varphi_s^*}^{\infty} \varphi^{(\sigma-1)} \frac{g(\varphi)}{1 - G(\varphi_s^*)} \mathrm{d}\varphi \right]^{\frac{1}{(\sigma-1)}} \tag{D.7}$$

We follow Bernard et al. (2007b) in assuming a Pareto distribution and follow their notation and parameter choices to write average productivity as a function of the productivity cut-off and Pareto parameters:[3]

$$\tilde{\varphi}_s = \left(\frac{c}{\gamma}\right)^{\frac{1}{\sigma-1}} \varphi_s^* \tag{D.8}$$

and to write the productivity cut-off (using the Free Entry condition and Pareto assumption) as:

$$\varphi_s^* = \left(\frac{f_s}{f_{es}}\right)^{\frac{1}{c}} \left[\frac{1}{\delta} \left(\frac{c}{\gamma - 1} \right) \kappa^c \right]^{\frac{1}{c}} \tag{D.9}$$

where c is the Pareto "shape" parameter, and $\kappa$is the Pareto "scale" parameter – the lowest possible draw value. To ensure that the distribution variance is finite, we follow Bernard et al. (2007b) in assuming that $c > \sigma - 1$. Finally, $\gamma = c - \sigma + 1$ which is devised to that both productivity and firm revenue follow a Pareto distribution.

[3]Which can also be used to further simplify the mass of firms condition, (D.5).

We can now re-write the mass of firms condition, (D.5), as

$$M_s = \frac{\lambda_s}{f_s \cdot \tau_s^{\alpha_s}} \tag{D.10}$$

where $\lambda_s = \frac{\eta_s R}{\left(\frac{c}{\gamma}\right)\sigma(w^{1-\beta_s} i^{\beta_s} \nu_s)^{1-\alpha_s}\zeta_s}$.

We can re-write the average emissions intensity as

$$e(\tilde{\varphi}_s) = \left(\frac{\Omega_s}{\lambda_s^{\frac{1}{\rho}}}\right) \cdot \frac{f_s^{\frac{1}{\rho}-\frac{1}{c}}}{\tau_s^{(1-\alpha_s)-\frac{\alpha_s}{\rho}}} \tag{D.11}$$

where $\Omega_s = \frac{\left(w^{1-\beta_s} i^{\beta_s} \nu_s \frac{\alpha_s}{1-\alpha_s}\right)^{1-\alpha_s} \cdot f_{es} \cdot \delta}{\left(\frac{c}{\gamma}\right)^{\frac{1}{\sigma-1}} \rho\left[\left(\frac{c}{\gamma}-1\right)\kappa^c\right]^{\frac{1}{c}}}$, and together, these two expressions yield the aggregate emissions intensity expression:

$$AEI_s = \left(\frac{\Omega_s}{\lambda_s^{\frac{1}{\sigma-1}}}\right) \frac{f_s^{\frac{1}{\sigma-1}-\frac{1}{c}}}{\tau_s^{1-\frac{\alpha_s}{\rho}}} \tag{D.12}$$

AEI is increasing in fixed production costs, f_s, working through a reduction in the mass of firms and increases in market concentration, but decreasing in fixed costs working through increases in the productivity cut-off and average productivity, the assumption that $c > \sigma - 1$ implies that the latter effect dominates. A rise in the emissions tax lowers AEI under the assumption that $\rho > \alpha_s$. While little empirical evidence exists that can shed light on our assumption,Oberfield and Raval (2014) provides an average estimate of σ which implies that $\rho \equiv \frac{\sigma-1}{\sigma}$ may be around 0.78, and a working paper by Shapiro and Walker (2015) using a model framework related to ours, estimate that α is around 0.011 on average for US manufacturers. These two empirical findings suggest that our parameter assumption is likely innocuous.

Alternative Measure of Environmental Stringency: PACE

The second measure of environmental stringency we devise relies on the theoretical framework regarding firm's choice of their abatement share, θ_s. As above, firms choose an abatement share that minimizes costs so that in equilibrium, the firm's choice of abatement share will be given by (D.2).

The variable θ_s is the share of a firm's resources, or share of gross output, g_s, that they choose to devote to abatement: $\theta_s = \frac{abatement_s}{g_s}$, and gross output is merely the sum of a given firm's net output plus their abatement investment: $g_s = q_s + abatement_s$. Thus, the

value of gross output (which is not observed) is captured by the sum of the firm's sales and amount spent on abatement expenditures. Since the choice of θ_s is independent of the firm's productivity level, this is consequently also the optimal choice at the sector level. We can thus relate the ratio of sector abatement and sales to three key factor costs:

$$\frac{\text{Abatement}_\text{s}}{R_s} = \left(\frac{\tau_s}{w^{1-\beta_s} i^{\beta_s} \nu_s} \frac{1-\alpha_s}{\alpha_s} \right)^{\alpha_s} - 1 \tag{D.13}$$

where R_s are sector revenues.[4]

We then estimate the following log-linear version of (D.13) for each sector, s, in year, t and predict the residuals:

$$\ln\left(\frac{\text{AbateExpend}_\text{st}}{R_{st}}\right) = \beta_0 + \beta_1 \ln(w_{st}) + \beta_2 \ln(i_{st}) + \underbrace{\ln(\tau_{st}) + \varepsilon_{st}}_{\text{Unobserved}} \tag{D.14}$$

The predicted residuals contain the factors driving firms' abatement observed share decisions apart from market wages and rental rates, in particular the unobserved, and thus implicit, environmental tax and abatement technology parameters. Of course the predicted residual from this estimation technique also contains all other unobserved factors influencing the observed abatement share decision, including measurement error, but we argue, in line with previous literature, that capital and labor costs comprise the largest share of additional factors that firms consider when making abatement share decisions. In addition, as discussed in Levinson and Taylor (2008), the use of PACE data does not include observations from the least productive and most emissions intense producers who dropped out of the market in the period preceding the year the PACE survey was conducted. Thus, if we find, using the PACE data, that more stringent environmental policy is associated with lower emissions or aggregate emissions intensity, our estimates will necessarily be a lower bound on the environmental effect, since the most emissions-intense polluters may have exited the sample for the year in question.

The wage and rental rates are taken from Atalay et al. (2014). Abatement expenditures are taken from the EPA's Pollution Abatement Cost and Expenditure survey,[5] and sector revenue data come from the NBER-CES database. Using this measure, the average implicit cost of environmental regulation rose roughly 17 percent from 1990 to 1994.

[4]We assume that the construction of the left hand side variable with nominal values in the numerator and denominator–which correspond to available data– yields results equivalent to a ratio of real output and abatement–from the theory.

[5]We thank Arik Levinson for making available a digital version of earlier years this data.

Appendix E

Chapter 3 Figures and Tables

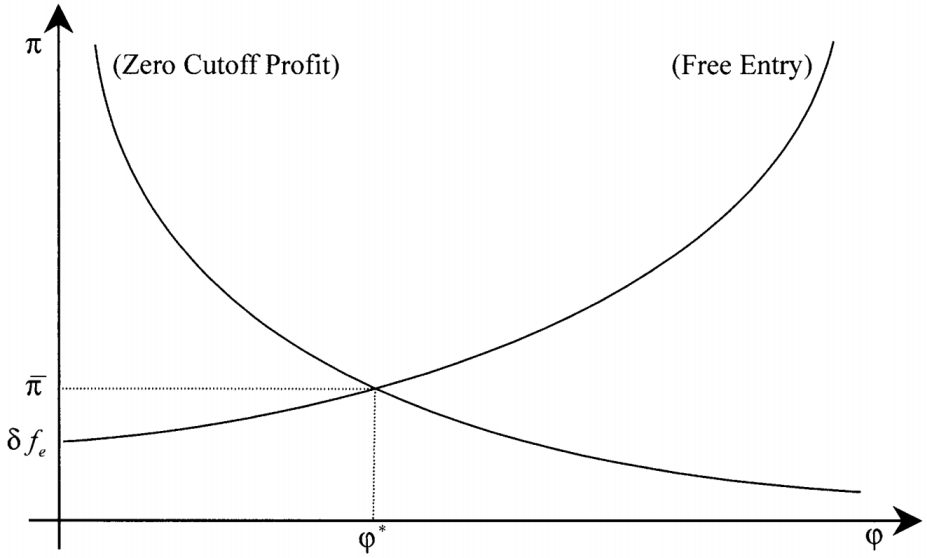


Figure E.1: Within and Across Sector Variation in Emissions: NEI, SO2 (All Sectors, Sector Groups)
Note: This figure is taken from Melitz (2003).

Table E.1: Summary Statistics: Dependent Variables

Dependent Variables	mean	sd	min	max
ModeledPounds (in thousands)	2,874	11,277	0.00093	221,310
Emissions Intensity	627	2,876	0.000065	64,201
Total Number of Firms	716	1,875	0	27,165
Average Firm Emissions Intensity*	446	1,492	0.00025	22,290
Herfindahl-Hirschman Index	0.0020	0.0031	5.9e-06	0.034
5-factor TFP Index	1.09	1.33	0.39	49.0
Independent Variables				
Sales Revenue(in $1m)	8,501	19,994	26.8	571,314
Non-Attainment Sales Share (Enviro. Reg.$_{NASS}$)	55.5	21.2	0.20	100
Non-Prod. Workers Per Firm (FC)	38.8	156	0	4,250
Panel: 1990 - 2007				

Note: All variables are gathered at the SIC4 level. "ModeledPounds" is a broad measure of toxic pollution emissions taken from the EPA's RSEI database. "Emissions Intensity" is calculated as ModeledPounds divided by real sector output, which is calculated using sales and price-index data taken from the NBER-CES database. "Total Number of Firms" are taken from the U.S. Census Bureau's Statistics of U.S. Businesses survey. "Average Emissions Intensity" are a sales-weighted average of firm-level emissions intensity calculated using firm sales data from the NETS database matched to emissions data from the RSEI database. The "Herfindahl-Hershcman Index" is a measure of industry concentration. The measure is described in detail in the text. The "TFP Index" measure is taken from the NBER-CES database. "Sales Revenue" are taken from the NBER-CES database. "Non-Attainment Sales Share (Enviro. Reg.$_{NASS}$)" is the share of industry sales subject to Non-Attainment. This regulatory measures is described in detail in the text. "Non-Prod. Workers Per Firm" is calculated as the ratio of non-production workers to total number of firms, in each sector. This measure proxies for fixed costs following Helpman, Melitz, Yeaple (AER, 2004). Sector total employment and the number of non-production workers is taken from the NBER-CES database.

*The firm-level data used to calculate the Average Emissions Intensity measure is only available through 2006.

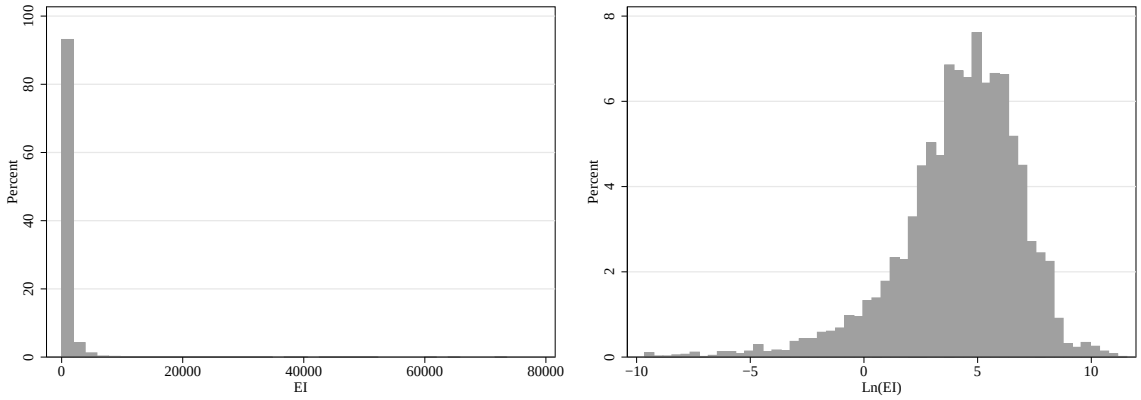


Figure E.2: Distribution of Emission Intensity

Note: The first figure presents the distribution of Emissions Intensity, measured as the ratio of ModeledPounds (of manufacturing establishments in the RSEI database from 1990 to 2006) to real output. Real output is calculated from sales and price index data in the NBER-CES database. Roughly 80-percent of sectors in the sample emit less than 475 pounds. 23 sectors emit zero at some point in the sample (79 observations in total). The second figure presents the distribution of emissions intensity data in logs.

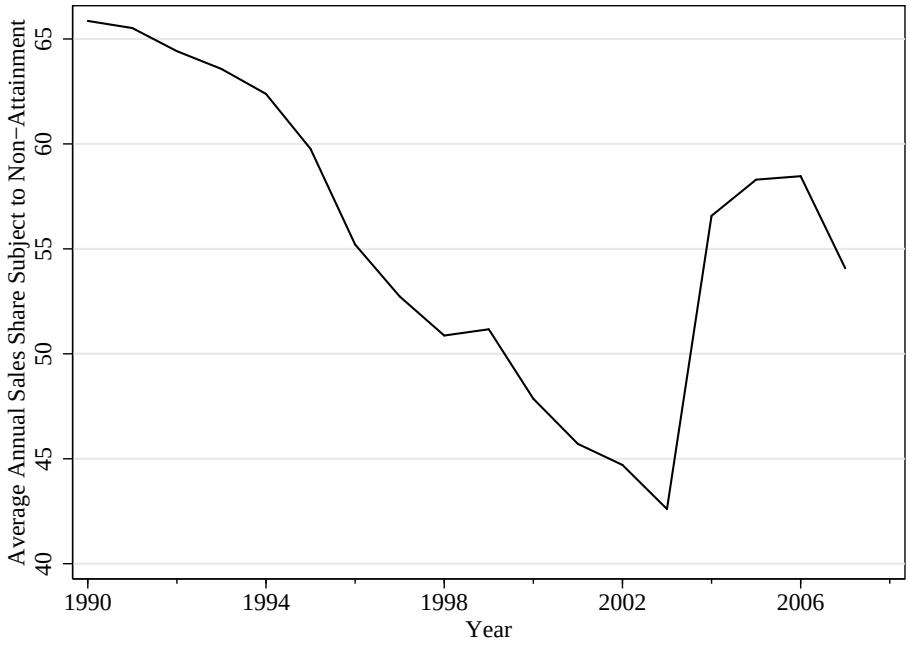


Figure E.3: Evolution of Average Non-Attainment Share Over Sample Period

Note: This figure plots the evolution of average environmental stringency, as measures by "Non-Attainment Sales Share," over the sample period. The sharp increase in 2004 is due to the implementation of a new non-attainment cutoff value for 8-hour Ozone. When implemented, in 2004, roughly 400 counties entered non-attainment.

Table E.2: Evaluation of Environmental Regulation Measure

	ModeledPounds	
	(1)	(2)
Sales	0.89***	0.82***
	(0.10)	(0.17)
Enviro. Reg.$_{NASS}$	-0.38**	-0.16*
	(0.17)	(0.087)
Constant	7.70***	7.54***
	(1.07)	(1.51)
Observations	7,093	7,093
R^2	0.190	0.317
SIC4 FE	NO	YES
Year FE	YES	YES
Number of sic		430

Note: Dependent Variable: ModeledPounds is taken from the EPA's RSEI database. Sales Revenue are measured in \$1m taken from the NBER-CES database. Enviro. Reg.$_{NASS}$ is the share of industry sales subject to Non-Attainment. This regulatory measure is described in detail in the text. All variables measured in natural logs. *** p<0.01, ** p<0.05, * p<0.1 Robust standard errors, clustered by SIC4, are in parentheses.

Table E.3: Evaluation of Fixed Cost Measure

	Number of Firms		HHI		TFP	
	(1)	(2)	(3)	(4)	(5)	(6)
FC	-0.70***	-0.62***	0.30***	0.10***	0.010	0.020**
FC	-0.63***	-0.62***	0.39***	0.077***	0.016	0.025**
	(0.061)	(0.073)	(0.059)	(0.024)	(0.013)	(0.010)
Constant	7.48***	7.43***	-8.04***	-7.08***	-0.054	-0.080***
	(0.20)	(0.23)	(0.19)	(0.074)	(0.040)	(0.030)
Observations	7,967	7,967	7,967	7,967	7,967	7,967
R^2	0.216	0.520	0.099	0.027	0.015	0.034
SIC4 FE	NO	YES	NO	YES	NO	YES
Year FE	YES	YES	YES	YES	YES	YES
Number of sic		459		459		459

Note: Fixed Costs (FC) are measured as the ratio of non-production workers, from the NBER-CES database, to the number of firms, taken from the US Census, in each SIC4 industry. HHI is a Herfindahl-Hirschman Index calculated using firm-level sales data from the NETS database.TFP is a total factor productivity index taken from the NBER-CES database. Panel extends from 1990 - 2007. All variables measured in natural logs. *** p<0.01, ** p<0.05, * p<0.1 Robust standard errors, clustered by SIC4 are in parentheses.
We also constructed the HHI using employment data from the NETS database. The coefficient magnitudes, signs, and significance levels are similar (available upon request).

Table E.4: Hypotheses 1 and 2: Regulation, Fixed Costs and Aggregate Emissions Intensity

	Aggregate Emissions Intensity							
	Level-Level				Log-Log			
	OLS	FE	AME		OLS	FE	AME	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Enviro. Reg.$_{NASS}$	-9.17	-6.71	-12.4*	-6.84				
	(6.80)	(12.0)	(7.43)	(12.0)				
FC	6.05	0.46	1.87	0.29				
	(6.44)	(0.84)	(2.01)	(0.51)				
Enviro. Reg.$_{NASS}$ # FC	-0.076	-0.0030						
	(0.080)	(0.0079)						
Enviro. Reg.$_{NASS}$					0.45	-0.58**	-0.28	-0.25**
					(0.63)	(0.28)	(0.20)	(0.11)
FC					0.90	-0.41	-0.034	0.010
					(0.70)	(0.28)	(0.12)	(0.080)
Enviro. Reg.$_{NASS}$ # FC					-0.24	0.11*		
					(0.17)	(0.065)		
Constant	1,572***	1,517*			3.77	7.83***		
	(500)	(790)			(2.63)	(1.16)		
Observations	6,934	6,934	6,934	6,934	6,934	6,934	6,934	6,934
R^2	0.020	0.040			0.078	0.324		
SIC4 FE	NO	YES	NO	YES	NO	YES	NO	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
Number of sic		430				430		

Note: Columns (1) and (2) present results from OLS and Fixed Effects regressions. Columns (3) and (4) present the average marginal effects (AME) for those two specifications. Columns (5) - (8) repeat this analysis with the data measured in logs.
Dependent variable: Aggregate Emissions Intensity is the ratio of SIC4 emissions, taken from the RSEI database, to real output, calculated using sales and pricing data from the NBER-CES database. Environmental stringency (Enviro. Reg.$_{NASS}$) is given by the share of industry sales, from the NETS database, subject to Non-Attainment. This regulatory measure is described in detail in the text. Fixed Cost (FC) is the ratio of non-production workers, taken from the NBER-CES database, to the number of firms, taken from the US Census, in each SIC4 industry. *** p<0.01, ** p<0.05, * p<0.1 Robust standard errors, clustered by SIC4, are in parentheses. Standard errors for the average marginal effects were calculated using the delta method.

Table E.5: Hypotheses 3 and 4: Regulation, Fixed Costs and the Mass of Firms

	Mass of Firms							
	Level-Level				Log-Log			
	OLS	FE	AME		OLS	FE	AME	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Enviro. Reg.$_{NASS}$	5.15*	-0.19	5.69*	-0.22				
	(3.07)	(0.37)	(2.92)	(0.36)				
FC	-1.72	-0.45***	-0.95**	-0.48***				
	(1.06)	(0.14)	(0.47)	(0.12)				
Enviro. Reg.$_{NASS}$ # FC	0.014	-0.00059						
	(0.011)	(0.00072)						
Enviro. Reg.$_{NASS}$					0.15	-0.096	0.46***	-0.047**
					(0.33)	(0.059)	(0.100)	(0.020)
FC					-1.01***	-0.68***	-0.61***	-0.62***
					(0.34)	(0.075)	(0.059)	(0.072)
Enviro. Reg.$_{NASS}$ # FC					0.10	0.017		
					(0.085)	(0.015)		
Constant	366**	673***			6.71***	7.83***		
	(180)	(27.1)			(1.33)	(0.28)		
Observations	7,968	7,968	7,968	7,968	7,967	7,967	7,967	7,967
R^2	0.008	0.042			0.262	0.522		
SIC4 FE	NO	YES	NO	YES	NO	YES	NO	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
Number of sic		459				459		

Note: Columns (1) and (2) present results from OLS and Fixed Effects regressions. Columns (3) and (4) present the average marginal effects (AME) for those two specifications. Columns (5) - (8) repeat this analysis with the data measured in logs.
Dependent variable: Number of firms, taken from the US Census, in each SIC4 industry. Environmental stringency (Enviro. Reg.$_{NASS}$) is given by the share of industry sales, from the NETS database, subject to Non-Attainment. This regulatory measure is described in detail in the text. Fixed Cost (FC) is the ratio of non-production workers, taken from the NBER-CES database, to the number of firms, taken from the US Census, in each SIC4 industry. *** p<0.01, ** p<0.05, * p<0.1 Robust standard errors, clustered by SIC4, are in parentheses. Standard errors for the average marginal effects were calculated using the delta method.

Table E.6: Hypotheses 5 and 6: Regulation, Fixed Costs and Average Emissions Intensity

	Average Emissions Intensity							
	Level-Level				Log-Log			
	OLS	FE	AME		OLS	FE	AME	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Enviro. Reg.$_{NASS}$	-1.63	-5.00	-3.82	-5.14				
	(2.82)	(4.62)	(3.00)	(4.75)				
FC	4.37	0.58	1.50	0.40				
	(3.48)	(0.74)	(1.20)	(0.45)				
Enviro. Reg.$_{NASS}$ # FC	-0.052	-0.0034						
	(0.041)	(0.0071)						
Enviro. Reg.$_{NASS}$					0.069	-0.55**	-0.17	-0.27***
					(0.69)	(0.27)	(0.23)	(0.098)
FC					0.61	-0.15	0.30**	0.21**
					(0.70)	(0.34)	(0.13)	(0.097)
Enviro. Reg.$_{NASS}$ # FC					-0.079	0.092		
					(0.17)	(0.075)		
Constant	867***	1,176***			3.63	6.55***		
	(204)	(311)			(2.83)	(1.17)		
Observations	6,391	6,391	6,391	6,391	6,391	6,391	6,391	6,391
R^2	0.033	0.110			0.078	0.325		
SIC4 FE	NO	YES	NO	YES	NO	YES	NO	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
Number of sic		421				421		

Note: Columns (1) and (2) present results from OLS and Fixed Effects regressions. Columns (3) and (4) present the average marginal effects (AME) for those two specifications. Columns (5) - (8) repeat this analysis with the data measured in logs.
Dependent variable: Average firm-level emissions-intensity, is the sales-weighted average of firms' emissions intensity. Firm emissions are taken from the RSEI database and matched to sales data in the NETS database. Real output is calculated using sector-specific price indices from the NBER-CES database. Environmental stringency (Enviro. Reg.$_{NASS}$) is given by the share of industry sales, from the NETS database, subject to Non-Attainment. This regulatory measure is described in detail in the text. Fixed Cost (FC) is the ratio of non-production workers, taken from the NBER-CES database, to the number of firms, taken from the US Census, in each SIC4 industry. *** p<0.01, ** p<0.05, * p<0.1 Robust standard errors, clustered by SIC4, are in parentheses. Standard errors for the average marginal effects were calculated using the delta method.

Table E.7: Summary Statistics for Fixed Cost and Environmental Regulation

	N	mean	sd	min	max
FC: Non-Prod. Workers Per Firm	7,968	38.80	155.73	0.0	4,250
FC2: Share Non-Prod. Workers	7,968	0.0	0.01	0.0	0.21
FC3: Capital Resalability Index	8,262	0.09	0.05	0.0	0.35
Enviro. Reg.$_{PACE}$	1,970	0.06	0.02	0.03	0.18

Note: "Non-Prod. Workers Per Firm" is calculated as the ratio of non-production workers to total number of firms, in each sector. This measure follows Helpman, Melitz, Yeaple (AER, 2005). "Share Non-Prod. Workers" is calculated as the ratio of non-production workers to total employment per firm, in each sector. This measure follows Syverson (ReStat, 2004). Sector total employment and the number of non-production workers is taken from the NBER-CES database. Number of firms is gathered from the U.S. Census Bureau's Statistics of U.S. Businesses survey. "Capital Resalability Index" (CRI) is the ratio of used capital expenditure to total capital expenditure. This measure is taken from Balasubramanian and Sivadasan (ReStat, 2009) and has been made publicly available by the authors. The data they use are only available for the 1988 and 1992 census years. The CRI measure used here is an average of the data from 1988 and 1992. "Enviro. Reg.$_{PACE}$" is an implicit environmental tax, described in detail in the text, that is estimated using data from the EPA's PACE survey, and wage and rental rate data from Atalay, Hortasu, and Syverson (AER, 2014).

Table E.8: Three Measures of Fixed Costs on: Number of Firms, HHI, TFP

	Number of Firms (1-6)						HHI (7-12)						TFP (13-18)					
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
FC	-0.63***			-0.62***			0.39***			0.077***			0.016			0.025**		
	(0.061)			(0.073)			(0.059)			(0.024)			(0.013)			(0.010)		
FC2		-0.95***			-0.79***			-0.44***			-0.12***			0.0012			-0.036***	
		(0.012)			(0.040)			(0.036)			(0.041)			(0.0012)			(0.012)	
FC3			0.60***						0.046						-0.012			
			(0.065)						(0.070)						(0.0086)			
Constant	7.48***	-1.01***	7.16***	7.43***	0.064		-8.04***	-9.87***	-6.71***	-7.08***	-7.69***		-0.054***	0.0022	-0.036***	-0.080***	-0.25***	
	(0.072)	(0.029)	(0.070)	(0.23)	(0.27)	(0.013)	(0.069)	(0.082)	(0.069)	(0.074)	(0.28)	(0.012)	(0.012)	(0.012)	(0.0078)	(0.030)	(0.085)	(0.0078)
Observations	7,967	7,967	7,994	7,967	7,967		7,967	7,967	8,190	7,967	7,967		7,967	7,967	8,097	7,967	7,967	
R^2	0.216	0.912	0.144	0.520	0.850		0.099	0.236	0.002	0.027	0.044		0.015	0.010	0.011	0.034	0.039	
SIC4 FE	NO	NO	NO	YES	YES		NO	NO	NO	YES	YES		NO	NO	NO	YES	YES	
Year FE	YES	YES	YES	YES	YES		YES	YES	YES	YES	YES		YES	YES	YES	YES	YES	
Number of SIC4				459	459					459	459	455				459	459	

Note: The dependent Number of Firms is gathered from the U.S. Census Bureau's Statistics of U.S. Businesses survey. The dependent HHI (Herfindahl-Hirschman Index) is the sum of market-share-squared for each firm, n, in a given sector, s. The dependent TFP is a productivity index taken from the NBER-CES database. The fixed cost measures are described in more detail under the previous descriptive statistics table. "FC" corresponds to "Non-Prod. Workers Per Firm" . "FC2" corresponds to "Share Non-Prod. Workers". "FC3" corresponds to "Capital Resalability Index." Because it only overlaps the emissions data for a single year, the inclusion of sector fixed effects soaks up all of the available variation in this measure. All variables are measured in natural logs. *** p<0.01, ** p<0.05, * p<0.1 Robust standard errors, clustered by SIC4, are in parentheses.

Table E.9: Alternative Measure of Environmental Stringency: PACE

	Emissions		Emissions Intensity							
	Log-Log		Level-Level				Log-Log			
			OLS	FE	AME		OLS	FE	AME	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Sales	0.80***	0.70***								
	(0.12)	(0.22)								
Enviro. Reg.$_{PACE}$	-0.41	-0.33**								
	(0.32)	(0.13)								
Enviro. Reg.$_{PACE}$			484	146	-10,252***	2,228				
			(3,474)	(2,988)	(3,513)	(2,789)				
FC			27.1***	-4.82	14.0***	-2.29				
			(3.19)	(5.80)	(1.65)	(2.72)				
Enviro. Reg.$_{PACE}$ # FC			-225***	43.5						
			(26.8)	(53.1)						
Enviro. Reg.$_{PACE}$							-1.23**	1.74***	-0.68***	-0.37***
							(0.49)	(0.61)	(0.16)	(0.14)
FC							0.60	-1.92***	0.096	0.031
							(0.40)	(0.55)	(0.064)	(0.16)
Enviro. Reg.$_{PACE}$ # FC							0.17	-0.67***		
							(0.14)	(0.19)		
Constant	5.68***	6.81***	343	1,136***			1.43	10.5***		
	(0.78)	(1.73)	(265)	(232)			(1.41)	(1.77)		
Observations	1,886	1,886	1,886	1,886	1,886	1,886	1,886	1,886	1,886	1,886
R^2	0.118	0.166	0.038	0.027			0.022	0.211		
SIC4 FE	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Number of SIC4		406		406				406		

Note: Columns (1) and (2) present results, with and without fixed effects, of a regression of sector emissions (ModeledPounds), taken from the RSEI database, on sector revenue (Sales) , taken from the NBER-CES database, and an implicit environmental tax (Enviro. Reg.$_{PACE}$), described in detail in the text, that is estimated using data from the EPA's PACE survey, and wage and rental rate data from Atalay et al. (2014). Data are in logs.
Columns (3) and (4) present results using OLS and Fixed Effects regressions of Emissions Intensity on fixed costs (FC) and the implicit environmental tax. Columns (5) and (6) present the average marginal effects (AME) for those two specifications. Data are in levels.
Columns (7) - (10) repeat this analysis with the data measured in logs.
Dependent variables: Emissions is the sum of establishment ModeledPounds by SIC4 sector, taken from the RSEI database. Emissions Intensity is the ratio of SIC4 emissions, from the RSEI database, to real output. Real output is calculated using sales and pricing data in the NBER-CES database. Fixed Cost (FC) is measured as the ratio of non-production workers, from the NBER-CES database, to the number of firms, taken from the US Census. The panel extends from 1990 - 1994.
*** p<0.01, ** p<0.05, * p<0.1 Robust standard errors, clustered by SIC4, are in parentheses. Standard errors for the average marginal effects were calculated using the delta method.

Table E.10: Augmented Specification Including Capital Intensity

	Level-Level				Log-Log			
	OLS	FE	AME		OLS	FE	AME	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Enviro. Reg.$_{NASS}$	4.45	-8.87	-11.0*	-6.90				
	(4.33)	(9.67)	(5.83)	(11.8)				
FC	4.37	0.53	1.61	0.63				
	(5.34)	(0.81)	(2.15)	(0.82)				
Enviro. Reg.$_{NASS}$ # FC	-0.065	-0.013						
	(0.081)	(0.016)						
KL	123**	-15.8	42.4***	5.34				
	(59.6)	(20.6)	(15.2)	(3.90)				
KL # Enviro. Reg.$_{NASS}$	-1.54	0.31						
	(0.96)	(0.39)						
KL # FC	0.099	0.10						
	(0.22)	(0.11)						
Enviro. Reg.$_{NASS}$					0.42	-0.31	-0.34*	-0.22**
					(0.65)	(0.29)	(0.20)	(0.11)
FC					0.13	-0.15	-0.24*	0.010
					(0.68)	(0.30)	(0.12)	(0.078)
Enviro. Reg.$_{NASS}$ # FC					-0.14	0.15**		
					(0.16)	(0.064)		
KL					0.94	1.56***	0.50***	-0.0082
					(0.98)	(0.42)	(0.15)	(0.093)
KL # Enviro. Reg.$_{NASS}$					-0.19	-0.21***		
					(0.22)	(0.081)		
KL # FC					0.10	-0.25***		
					(0.12)	(0.071)		
Constant	554**	1,622**			4.36	5.57***		
	(259)	(658)			(2.74)	(1.32)		
Observations	6,934	6,934	6,934	6,934	6,934	6,934	6,934	6,934
R^2	0.068	0.044			0.101	0.332		
SIC4 FE	NO	YES	NO	YES	NO	YES	NO	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
Number of SIC4		430				430		

Note: Columns (1) and (2) present the regression results using OLS and Fixed Effects regressions. Columns (3) and (4) present the average marginal effects (AME) for those two specifications. Columns (5) - (8) repeat the analysis, with the data measured in logs.
Dependent variable: Aggregate Emissions Intensity is the ratio of SIC4 emissions, from the RSEI database, to real output. Real output is calculated using sales and pricing data in the NBER-CES database. Environmental stringency (Enviro. Reg.$_{NASS}$) is given by the share of industry sales, from the NETS database, subject to Non-Attainment. This regulatory measure is described in detail in the text. Fixed Cost (FC) is the ratio of non-production workers, taken from the NBER-CES database, to the number of firms, taken from the US Census, in each SIC4 industry. The capital-labor ratio (KL) is calculated as the ratio of investment to employment in each SIC4 sector, taken from the NBER-CES database. *** p<0.01, ** p<0.05, * p<0.1 Robust standard errors, clustered by SIC4, are in parentheses. Standard errors for the average marginal effects were calculated using the delta method.

Vita

Lawrence Dale LaPlue, III was born to Larry and Darlene LaPlue in Bethesda, MD on April 4, 1986. In 1999 he moved to Morristown, Tennessee and graduated from Berean Christian High School in 2004. He then moved to Dayton, TN where he attended Bryan College until graduating suma cum laude in May 2008 with a Bachelor of Arts in History and a Bachelor of Arts in Political Communication. He moved back to Morristown, Tennessee later that year to begin work at ES, Incorporated as a technician, IT manager, and later project manager. He married his wife, Victoria Carol, in July 2010 and moved to Knoxville, Tennessee in 2011 to begin his graduate studies at the University of Tennessee. He received his Master of Arts degree in Economics in December 2012 and his Doctor of Philosophy degree in Economics in August 2016. His resarch work focusses on international trade and environmental policy, specifically examining the degree to which within and across sector forces are driving changes in our environment. He has presented his research at conferences and Universities across the United States as well as the Federal Reserve in Atlanta. He has taught undergraduate courses in macroeconomics, trade and development to students at the University of Tennessee. This fall, he and his wife, Victoria, and their two children will move to Las Cruces, New Mexico, where he has accepted a position as an Assistant Professor of Economics in the Department of Economics at New Mexico State University.