Does the EU ETS Cause Carbon Leakage in European Manufacturing? A Sector-Level Analysis

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Carbon leakage is an issue of major interest in both the academic and policy debates about the effectiveness of climate policy in the context of global asymmetries in climate policy coverage. The debate is particularly salient in Europe, where the EU Emissions Trading System (EU ETS) covers emissions of many traded sectors. We formulate a model that explains why each sector should be affected by carbon leakage according to its carbon intensity, more exactly the relative weight of regulation-induced carbon cost in its production function. This prediction can be tested empirically using data on trade flows, sectoral emission intensities and carbon prices. Using trade data for the period 2003-2014 at the 8-digit product-level, we test for the effect of carbon cost on import intensity. Our paper complements firm-level studies of production relocation by considering leakage more fully than possible in firm-level analysis. We do not find evidence in favor of a significant impact of carbon cost on trade flows and therefore conclude that the EU ETS has not caused carbon leakage during its first two trading phases.

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1 Introduction

As the international community struggles to find an international solution to global warming caused by anthropogenic carbon dioxide (CO_2) emissions, the EU has implemented carbon pricing unilaterally by establishing the EU Emissions Trading System (EU ETS). However, the EU ETS only covers about 4% of global greenhouse gas emissions (Ellerman et al., 2015). Regulating only a small part of the world's CO_2 emissions might simply move emissions to parts of the world with no climate regulation without solving the global climate problem – a phenomenon known as carbon leakage.[1] If carbon leakage were sizable, it would make EU climate policy efforts ineffective and moreover disadvantage European firms vis-à-vis their international competitors, potentially leading to job loss and economic downturn. This explains why the leakage question has become a key topic for research and policy makers. The leakage problem is recognized at the highest levels of EU decision making. It has been and continues to be the justification for providing compensation to manufacturing sectors regulated under the EU ETS. Currently this compensation is in the form of free allocation of emissions allowances. This may or may not have contributed to avoiding carbon leakage in Europe. Therefore, the question of whether the EU ETS has caused carbon leakage is of great interest for research and policy.

Carbon leakage can occur through different channels: (i) relocation, when firms shift their production from EU ETS-regulated sites to foreign countries, (ii) changes in market shares, when European firms lose their market shares to unregulated foreign competitors or (iii) indirectly through energy input prices, when falling energy prices due to strict regulation in Europe cause emission-intensive commodities to become cheaper overall and thus emissions to increase globally.[2] Some authors claim that "inverse" carbon leakage might occur through technology spill-over effects (di Maria and van der Werf, 2008; Gerlagh and Kuik, 2014; Schmidt and Heitzig, 2014). All of these channels translate directly into trade flows: for a given level of consumption of a carbon-intensive product, carbon leakage leads to a higher share of imports in total consumption. We therefore argue that a full answer to the question whether the EU ETS has caused carbon leakage requires an analysis at the sector or product-level. By definition, a firm-level analysis can only provide a partial answer to the leakage question, as it may only provide evidence on one

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[1] Carbon leakage is usually defined as the ratio of emission increase in the unregulated (rest of the world) region over the reduction in the regulated (EU) region (e.g. Aichele and Felbermayr, 2015; Antimiani et al., 2013; Demailly and Quirion, 2006; di Maria and van der Werf, 2008)

[2] The third leakage channel has been labeled"green paradox" (Harstad, 2012; Jensen et al., 2015).

aspect of leakage, namely relocation. While relocation is an important aspect of leakage, even without relocation of production by European firms leakage may occur through an increase in market shares of competing firms that produce in regions with no climate policy. Thus, our definition of carbon leakage includes both relocation of production by European firms and imports from foreign firms. Our approach can be viewed as complementary to analyzing leakage at the firm-level.

This paper addresses the research question of whether the introduction of the EU ETS has caused carbon leakage. Even before the establishment of the EU ETS, there already has been a literature arguing that environmental regulation reduces domestic firms' competitiveness and therefore displaces emissions rather than globally reducing them, usually called "pollution-haven" effect (e.g. Antweiler et al., 2001). Empirical evidence for such effects was usually scarce (e.g. Tobey, 1990; **?**; Jaffe et al., 1995). **?** is an exception to this rule as they find a small but significant impact of emission cost on US trade with Mexico and Canada over the 1980's.[3]

Today, the question remains controversial in the context of the EU ETS from both an academic and a policy perspective. Ex ante approaches predict carbon leakage, while ex post analyses typically fail to confirm these predictions. Ex ante studies are usually based on CGE models; Demailly and Quirion (2006, 2008) examine the impact on individual sectors (cement, iron, steel) and find positive carbon leakage rates. They show that output-based allocation avoids leakage, but also eliminates the incentive to abate emissions. The paper by Felder and Rutherford (1993) shows that even a moderate carbon policy has a carbon leakage rate of 25%, which passes mostly through oil prices. The official IPPC report (IPCC, 2007) quotes carbon leakage rates between 5% and 20%. Gerlagh and Kuik (2014) show that allowing for technology spill-overs may lead to "negative" carbon leakage.

Firm-level empirical ex post studies usually find that the EU ETS had a limited impact on firm competitiveness and on carbon leakage (Chan et al., 2013; Lacombe, 2008; Sartor, 2013). Martin et al. (2014) use a large survey to learn about relocation risk; given that optimal compensation (through grandfathering) should equalize marginal relocation risk across sectors, the current EU ETS rules largely over-allocate many sectors. Dechezlepretre et al. (2014) use a survey of multinational firms to examine intra-firm shifts of production location; they find no evidence for carbon leakage *within* firms.

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[3] Note that the early literature mostly did not use emission cost directly but rather the more indirect measure of "pollution abatement cost". This was mainly due to data availability concerns and might lead to biases as shown by Levinson and Taylor (2008).

Finally, a strand of literature examines trade flows at the sectoral level. For example, Sartor (2013) finds that the EU ETS has not led to carbon leakage in the aluminium sector; Branger et al. (2013) find no leakage in the cement and steel sector. A notable exception in the empirical literature is Aichele and Felbermayr (2015). Based on a "gravity model for carbon" they find that the carbon content of trade (at a sectoral level) was significantly impacted by the country's ratification of the Kyoto protocol, i.e. that ratifying Kyoto has led to carbon leakage. It remains however unclear, how through what channel the Kyoto protocol has induced this effect, given it has not been translated into taxes or emissions trading systems in most of the signatory states.

We contribute in several important ways to the literature evaluating ex post whether carbon leakage has occurred in the European manufacturing sector due to the introduction of the EU ETS. First, we focus on the EU ETS which is a clearly defined policy intervention, while the Kyoto Protocol had various implementations in different signatory countries. In particular, the EU ETS generates a clear price for CO_2 emissions. Second, by focusing on European trade with the rest of the world, we are able to use trade data at the product-level, so that we can exploit cross-sectoral variation more fully than e.g. Aichele and Felbermayr (2015) are able to do. Third, we consider emissions that went into each product comprehensively by exploiting data generated by the EU Commission's carbon benchmarking, which importantly cover all emissions including process emissions. Fourth, we complement the effects on relocation evaluated by firm-level studies, e.g. Martin et al. (2014) or Dechezlepretre et al. (2014), by considering the trade channel more fully, including imports by firms from regions with no climate policy. We focus on leakage through the trade of manufactured goods, leaving out green paradox type general equilibrium effects.

Using a reduced-form expression derived from our model, we estimate the effect of treatment intensity, as measured by the share of carbon cost in overall product value, on product-level carbon leakage, proxied by the change of imports over the change in domestic production. Our preliminary results indicate that that the EU ETS has not caused carbon leakage in European manufacturing. We therefore conclude that either the current level of compensation of manufacturing in the EU ETS has been sufficient to avoid carbon leakage so far, or that the leakage effect of the EU ETS is so small as to be outweighed by barriers to leakage inherent in monopolistic competition.

In the following, we first present our model and empirical strategy (Section 2), followed by the data (Section 3) and our results (Section 4). We conclude and outline further

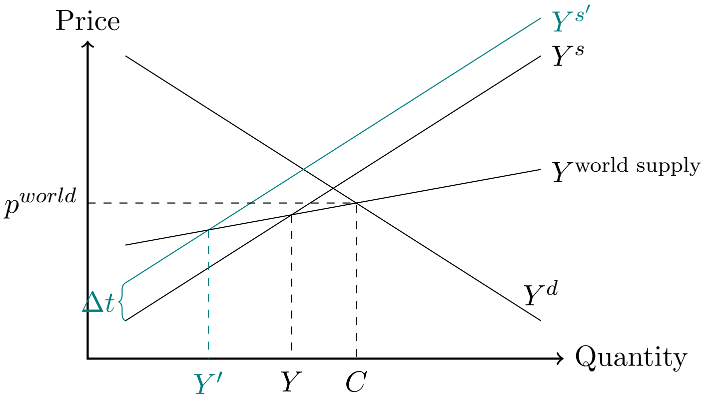

Figure 1: Textbook illustration

necessary steps in Section 6.

2 Model

In order to better understand the concept of carbon leakage, it is first useful to look at the most simple textbook illustration of the problem. In a simplistic case consumption C is constant when carbon cost t increases the good's (domestic) unit price, because the good is priced at the constant world price p^{world} anyways. The only effect of the environmental policy is an increase in imports from Q to Q' while the emissions stay constant[4]. Carbon leakage defined as the change in foreign emissions over the change in domestic emissions *due to the policy* is thus 100%: worldwide emissions have not changed because production has not been reduced but merely shifter from the regulated to the non-regulated region. In a more realistic model, substitution between domestic and foreign products is not perfect, so that overall consumption might not be constant, leading to carbon leakage rates below 1.

2.1 Krugman Trade Model between Two Regions

Underlying our analysis lies a stylized trade model à la Krugman (1980). Following Aichele and Felbermayr (2015), agents have a CES utility function with sector-specific elasticity σ^s.[5] We simplify by accounting only for trade between two regions, regulated and unregulated. Prices depend on the country's domestic prices p_i^s as well as the prices of imported goods which are the result of foreign prices multiplied by iceberg trade costs $\tau^s > 1$.

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[4] Assuming as in the remainder of the paper that carbon efficiency is about constant in different countries.

[5] See Appendix for whole model

Consumers spread their consumption over S differentiated goods sectors with constant expenditure shares μ^s. All sectors feature monopolistic competition, increasing returns to scale and free entry. The unit production cost for a firm depends on carbon cost and other factors normalized to 1. Carbon cost enters with a sector-specific Cobb-Douglas weighting β^s. In the unregulated part of the world, the carbon cost factor t_i is 1, i.e. carbon cost is not affecting production cost.[6]

$$C_i^s = c_i^s(t_i, w_i) + f \tag{1}$$

$$c_i^s(t_i, w_i) = c_i^s(t_i, 1) = (t_i)^{\beta^s} \tag{2}$$

Solving the model in a standard way, we get import quantities Q_d^s to domestic country d from foreign country f:

$$Q_d^s = \mu^s \omega \frac{L_d}{P_d^s} N_f^s \left(\frac{\tau^s p_f^s}{P_d^s} \right)^{-\sigma^s} \tag{3}$$

where the labor endowment divided by domestic prices L_d/P_d measures the domestic market capacity and the number of foreign varieties weighted by foreign prices $N_f p_f^{-\sigma}$ measures the foreign country's supply capacity. The (symmetric) trade cost is τ^s.

Let us define the unit CO2 requirement e^s, which following Shephard's Lemma will be $e^s = \partial c_d^s / \partial t_d = \beta^s c_d^s / t_d$. Our main parameter of interest will be the emission cost per unit relative to overall cost $\theta^s = e^s t_d / p_d^s = \beta^s(\sigma^s - 1)/\sigma^s$.[7]

Carbon leakage CL is defined as the change in foreign emissions over the change in domestic emissions *due to* carbon cost. From the Krugman model it follows that it is proportional to the change in the ratio Q_d/Y_d as well as to the change in $\theta^s t_d$. Using $\hat{x} = dx/x$ to denote percentage change in each variable, we have:

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[6] While a Cobb-Douglas production function *per se* is a restrictive assumption, Levinson and Taylor (2008) shows that this is equivalent to a situation where (a.) firms abate optimally given stringency of environmental policy and (b.) pollution abatement cost can be measured as a fraction of total factor use.

[7] Because $p_d^s = c_d^s \sigma^s / (\sigma^s - 1)$, see Appendix.

$$
\begin{aligned}
CL &= \frac{\partial(e_f(Q_{df}+Q_{ff}))/\partial t_d}{\partial(e_d(Q_{fd}+Q_{dd}))/\partial t_d}\hat{t}_d && (4)\\
&= \underbrace{(\beta(\sigma-1)}_{\text{direct competitivity effect}>0} - \underbrace{\frac{\kappa_{\lambda_d}}{\lambda_d})}_{\text{elasticity of market share } d<0} \quad \hat{t} && (5)\\
&= \beta(\sigma-1)(1+k)\hat{t} && (6)\\
&= (1+k')\theta\hat{t} && (7)\\
&\propto \frac{dQ_d}{dY_d} && (8)
\end{aligned}
$$

For an equal increase in carbon cost t_d, domestic sectors will be hit harder if their carbon intensity β^s is higher as well as if substitution elasticity σ^s is higher such that consumers substitute to foreign varieties more easily. Intuitively speaking, if a country introduces carbon taxes or other measures making carbon emissions costly, this increases emitting sector's variable production cost and thus decreases its supply capacity, so that the share of produced varieties $N_d/\bar{N} = \lambda_d$ and its exports should fall, as its cost c_d increases. As some consumption substitutes away to foreign goods, but not all, it also increases it's own price level p^s_d, and thus P^s_d. Relatively speaking, production which involves carbon emissions becomes less competitive in the regulated country which is then reflected by an increase in imports Q^s_d and a decrease in exports Q^s_f and production Y^s_d, i.e. carbon leakage CL^s, as well as a decrease in domestic market size M^s_d (through a wealth effect).[8] The magnitude of this effect depends on : (a) each sector's carbon intensity which enters production cost through β^s, (b) the sectoral elasticity of substitution σ^s and (c) the stringency of the environmental policy, i.e. the magnitude of the change in t_d.

L_d, τ^s, σ^s and μ^s are parameters that are assumed to be exogenous. By looking only at *changes* in the import-production ratio, we neutralize any pre-existing scale and competition effects and concentrate only on the impact of changes in t_d. We will thus examine how leakage CL evolves with fluctuating stringency of environmental policy, i.e. higher and lower carbon cost. We reject the hypothesis of no carbon leakage in case of a systematic link between the sector-level relative carbon cost and changes in the import share.

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[8] The environmental policy also affects the domestic consumption in the non-regulated country (Q_{ff}) but this indirect effect is numerically dominated by the effects on trade flows.

Our estimated equation is

$$\frac{dQ_d}{dY_d} = \alpha + \gamma\theta_{st}\hat{t}_d + \mu_t + \mu^s + \epsilon_{st} \tag{9}$$

where $\frac{dQ_d}{dY_d}$ is our proxy for carbon leakage, i.e. the change of imports over the change in domestic production, θ_{st} is the sector-specific importance of CO2 cost which is multiplied by the percentage change in per-tonne-CO2 cost. μ_t are year fixed effects accounting for business cycles and μ_s are sector fixed effects accounting for the normal level of technological advance and country sizes. Having controlled for fixed effects, the remaining variation in import intensity $\frac{dQ_d}{dY_d}$ only reflects sector-specific changes between the years, which should be partly explained by $\theta_{st}\hat{t}$ if there is carbon leakage. However, if there is no carbon leakage, $\theta_{st}\hat{t}$ should not have any explanatory power.

2.2 Identification

As in any empirical study, some important issues challenge identification. The most important here seem to be reverse causality, i.e. whether changes in import intensity determine CO2 prices, and omitted confounding variables, e.g. energy prices determining both the left-hand variable and the CO2 price.

The question of reverse causality seems unlikely in this case, because the bulk demand for CO2 certificates came from the electricity sector, with over 60% of total emissions in the EUTL in Phase II. None of the manufacturing sectors had emissions big enough to substantially influence the price of CO2 certificates.

A much more thorny question is the one of omitted common factors that would drive both CO2 price and imports. At first sight, energy prices would be an obvious candidate, but because these are mostly determined worldwide, they should impact foreign production as much as domestic production and should thus not affect our import intensity variable. Indirectly however, they could increase trade costs and thus make domestic production more attractive relative to imports (even though there is no reason that this effect is proportional to emission intensity). As an increase in energy prices generally decreases CO2 prices, the trade cost effect would thus indirectly bias our estimate of α upwards. As the central point of our paper is that we do not find any significant effect of α, this actually strengthens our claim.

Another issue arises if the EU increased energy taxes, this should decrease the demand for energy and thus for CO2 certificates, while at the same time making imports more attractive relative to domestic production. However, there has not been any substantial EU-wide increase in energy prices in the period we study.

2.3 Assumption: constant technology

In this research, we assume that the emission factors computed by the European Commission are a reasonable proxy for emission intensity within a sector. This assumes away the importance of sector heterogeneity that could lead to selection, as well as the impact of directed technical change.

On the second point, the literature largely agrees that the EU ETS has not had tremendous impact on technology change as Rogge (2016) asserts in her literature survey on this topic. There exist some sector-specific studies, which also do not find a significant impact of EU ETS on low-carbon innovation, e.g. Rogge et al. (2011) on pulp and paper or Schleich et al. (2010) on cement. Calel and Dechezlepretre (2016) find a significant increase in low-carbon patents by firms regulated under the EU ETS, but describe its magnitude as a “quite unremarkable nudge”.

2.4 Alternative specification

We justified the main estimation equation using a Krugman-style monopolistic competition trade model. Albeit this model is fairly standard in international economics, its functional form is restrictive and there have been alternative approaches, in particular also in the literature testing for the trade impact of environmental regulation.

Aichele and Felbermayr (2015) show themselves how the same functional form can also be derived by using an Armington-style model of national product differentiation rather than monopolistic competition as in the Krugman-Dixit-Stiglitz model laid out previously; this model would thus not change our main estimation equation.

The first important paper in this strand of literature is Tobey (1990) who is inspired by the Ricardian comparative advantage literature. He estimates net exports as a linear function of country endowments and a qualitative measure of environmental regulation stringency using ordinary least squares:

$$Q_{f,t} - Q_{d,t} = \alpha + \gamma d_t + \mu_s + \mu_t + \epsilon_{st} \tag{10}$$

where d_t is a qualitative measure of environmental stringency. We will estimate this equation using both carbon cost per produced unit $e^s t_d$ and carbon cost per unit value θ_d as sectoral proxies for this stringency. Tobey includes a list of country-specific factor endowments, but because we are in a two-country setting these can simply be captured by year fixed-effects. The treatment parameter then picks up only between-sector variation linked to carbon leakage.

Similarly, Branger et al. (2013) write down the most simple two-country perfect competition trade model, which yields the result that net imports are a function of CO2 cost over price. In their estimation they carefully control for auto-correlation of net imports by using an ARIMA(p,1,q) approach.

$$Q_{d,t} - Q_{f,t} = \alpha_s t_{t-3} + \mu_t + \epsilon_{st} \tag{11}$$

where t_{t-3} is a three-month lag of carbon price.[9] Similarly to Tobey (1990), they include measures of EU industrial output, EU construction index and BRICS industrial output that will just be captured by year fixed-effects here. They show with an Augmented Dickey-Fuller test that all time series are I(1). In order to address this issue, the identify the ARIMA(p,1,q) process that suits each dependent variable by following the Box and Jenkins methodology.

Alternatively, one could also normalize each sector's net imports by the sector's domestic production. The dependent variable would then be the change in net imports over the change in domestic production:

$$\begin{align} i_{st} &:= \frac{d(Q_{d,t} - Q_{f,t})}{dY_{d,t}} \tag{12} \\ &= \alpha + \gamma \theta_{st} \hat{t} + \mu_s + \mu_t + \epsilon_{st} \tag{13} \end{align}$$

Or to normalize even more and be sure to not capture any size effects, we could look at percentage changes in percentages in order to account for multiplicative effects:

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[9] However, they find their results to be very robust to changes in the lag between 1 and 5 months.

$$\hat{i}_{st} := \frac{i_{st}}{(Q_{d,t} - Q_{f,t})/Y_{d,t}} \tag{14}$$

$$= \alpha + \gamma\theta_{st}\hat{t} + \mu_s + \mu_t + \epsilon_{st} \tag{15}$$

In the empirical section we will estimate all of these specifications, in order to show that our results are not driven by the choice of the (highly parametric) Krugman model.

3 Data

In order to evaluate the existence of carbon leakage at the sectoral level, we need information on international trade flows and on the relative carbon-cost at the sector-level. Our dataset covers the period 2003-2014 and enables us to evaluate the effect with and without the EU ETS. Trade data is provided by Eurostat's Comext database. We use import, export and production levels at the aggregate EU-27 level. Within-EU trade is not relevant in our context, as carbon leakage can only occur between the EU and the rest of the world. Trade data is available at the sectoral PRODCOM, which is relatively detailed 8-digit definition of products, e.g. it differentiates between paper for newspaper production, photographic prints and graphic paper. The trade data allow us to define our proxy for carbon leakage, the change in import intensity $\frac{dQ_d}{dY_d}$ for each year. Q_d^s is the EU import quantity and Y_f^s is domestic production at the sector-level each year.

Emission intensities are available at PRODCOM level from the benchmarking established by the Commission. It is only available for a subset of 86 sectors, all of which are process-regulated under the EU ETS. As such, they are not representative of the overall EU economy, but should be the sectors most affected by the EU ETS. This benchmark represents for each sector the average of the 10% most carbon-efficient firms. We thus know the CO_2 emissions per unit produced e^s (in tCO2/unit).

In order to transform emissions per unit to a relative carbon cost, we further need product price per unit p_d^s and the price of carbon t_d (in € per tCO2e). Price data for European carbon permits is readily available from trading platforms such as the ICE. Carbon cost per unit is thus $e^s t_d$. Relative carbon cost (in € carbon cost per € of product value) is the key variable that we will call treatment intensity θ^s and which is defined as the total CO_2 cost per unit e^s over the product price:

Table 1: Descriptive Statistics

	Obs	Mean	Std. Dev.	Min	Median	Max
Carbon price in €per ton	11	10.38	7.9	0	8.14	26
Carbon price, y-o-y change in percent	10	-33.0%	33.0%	-98.0%	-32.0%	15.0%
Tons of emissions per unit e^s	891	0.44	0.47	0.02	0.32	2.79
Cent of CO2 cost per unit $e^s t_d$	891	0.46	0.7	0	0.26	7.25
Treatment intensity in percent (2005-2014) θ^s	770	0.5	0.88	0	0.22	11.2
Treatment change $\theta^s \hat{t}$	713	-0.07	0.25	-3.17	-0.03	1.63
Import share Q_d/Y_d	751	18.35	49.66	-32.71	7.02	1207.52
Net import share	751	32.56	168.46	-225.3	-2.94	1945.24
Change import share dQ_d/dY_d	666	0.86	20.47	-33.84	0.02	522.22

Source: Eurostat, EU Commission, ICE, authors' calculations.

Note: treatment intensity only shown for 2005-2014, because it is zero before.

$$\theta_{st} = \frac{e^s t_d}{p_d^s}$$

Descriptive statistics are given in Table 1. For most goods, the relevant unit is the kilogram. Carbon cost per kg varies between virtually zero and 7 cent. Accounting for the value of products, we can compute the treatment intensity which varies between zero and 48%. 24 sectors (among 85 in total) have a θ greater than 1.8% which is the cut-off Tobey (1990) uses to define "carbon-intensive" industries. Import shares are 15% on average with considerable variation and large fluctuations: 90% of the sample have growth rates comprised in [-1,1], but some sectors more than double their import share from one year to the other.

By construction, treatment intensity θ^s is zero in the years before the EU ETS was introduced (2003 and 2004). Carbon emissions were free of charge for firms at this time, so the cost of embedded carbon was zero both in the EU and outside.

4 Results

A raw correlation analysis gives a first idea that the import share's evolution is not driven by the relative cost of embedded carbon θ^s (Table 2). Neither standard Pearson's correlation coefficient, nor the non-parametric rank-correlation measures Spearman's ρ and Kendall's τ are significantly different from zero. Including the "non-treated" years 2003-2004 when the EU ETS was not yet in place has no effect.

	Correlation	Spearman's ρ	Kendall's τ
dQ_d/dY_d with $\theta\hat{t}$			
Whole period (2004-2014)	-0.0659	-0.018	-0.0126
	(0.102)	(0.656)	(0.640)
excluding phase I (2008-2014)	-0.0766	-0.0134	-0.0094
	(0.195)	(0.763)	(0.752)
dQ_d/dY_d with θ			
Whole period (2004-2014)	0.0473	0.0182	0.0781
	(0.223)	(0.235)	(0.267)
excluding phase I (2008-2014)	0.0646	0.0135	0.0889
	(0.145)	(0.225)	(0.280)

Note: p-values in brackets

Table 2: Raw Correlation with the change in import share dQ_d/dY_d

	(1)	(2)	(3)	(4)
Treatment intensity	-534.393	-119.486	-107.327	-182.785
	(0.162)	(0.733)	(0.760)	(0.668)
Sector fixed effects	-	Yes	Yes	Yes
Linear trend	-	-	Yes	-
Year fixed effects		-	-	Yes
Obs	615	615	615	615
R2	0.0027	0.0136	0.0035	0.0043

Note: t-statistics in brackets below

Table 3: Estimation results, outcome is the change in import share dQ_d/dY_d

In a second step, we regress the change in import share on a constant, sector fixed effects and treatment intensity (Table 3, columns (2) - (4)). Again, we do not find any significant coefficient, which means that treatment intensity does not seem to significantly drive the trading patterns between EU and non-EU regions. This does not change if we account for time trends or yearly fixed-effects. Graphically, this is represented on Figure 2.

Based on preliminary results we do not find indications for carbon leakage. In our data, the cost of embedded carbon varies between 0.1% and almost 50% of the final product price, so that there is sufficient treatment variation. However, across different measures – ranging from correlations, over rank-correlations to regressions with sector fixed-effects – we do not find any statistical link between the evolution of import-intensity and the relative carbon-cost induced by the EU ETS. This result is not compatible with the hypothesis of carbon leakage: even if only some sectors suffer carbon leakage while some other sectors remain unaffected, the average correlation should be positive.

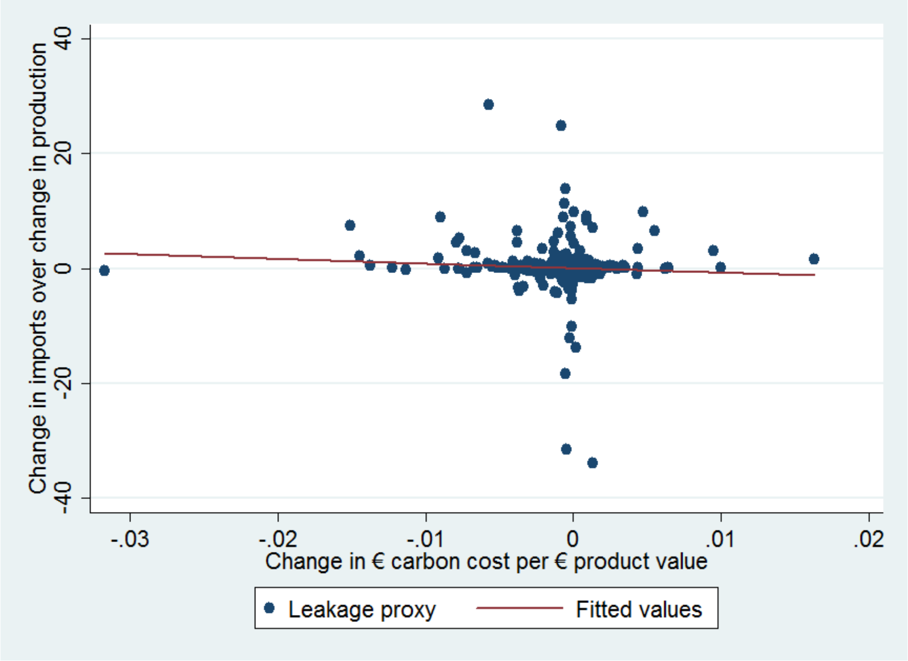

Figure 2: Growth in import share as a function of treatment intensity

	(1)	(2)	(3)	(4)	(5)
Outcome	Net exports	Net exports	Branger	Net import share change *i*	Net import share elasticity $\hat{i}$
Relative CO2 cost		82.471	xx	-110.020	935.033
		(0.722)	xx	(0.490)	(0.608)
Carbon cost per unit	74.78568				
	(0.826)				
Sector fixed effects	Yes	Yes		Yes	Yes
Year fixed effects	Yes	Yes		Yes	Yes

Note: t-statistics in brackets below

Table 4: Alternative specifications

5 Robustness

As shown in Table 4, none of the alternative specifications outlined in section show any significant impact of carbon cost on different measures of trade flows. While our main specification was chosen in order to be consistent with a Dixit-Stiglitz-Krugman trade model, other models yield other functional forms. However, the absence of significant evidence for leakage does not seem driven by this functional form assumptions.

6 Concluding Remarks and Further Steps

Our analysis concludes that the EU ETS has not induced carbon leakage in the European manufacturing sector, even though it is predicted by theory and ex ante simulation analyses. This is in line with previous empirical research, as for example Branger et al. (2013) call the debate about carbon leakage “much ado about nothing”.

The absence of trade effects suggests that barriers against carbon leakage exist which are not accounted for in the more stylized ex ante models. In particular one could note the relative importance of tariffs and transportation costs, which are in general higher than CO_2 related costs and contribute to firms’ ability to pass-through additional to the final consumer without losing significant market share. Additionally more diffuse factors such as political risk, exchange rate concerns and considerations about the availability of qualified labor probably limit relocation.

One the one hand, this is good news for the political feasibility of regional carbon policies such as the EU ETS even in a context of globally asymmetric climate policy. If they do not hamper domestic competitiveness and economic growth, they are much more likely to be implemented. On the other hand, this also means that the level of carbon cost currently imposed by the EU ETS does not seem to translate into higher product cost and thus does not redirect consumption towards sustainable, low-carbon products.

Further steps involve the consideration of carbon intensity of intermediate inputs, using input-output tables such as available from OECD[10]. Details for such a computation follow Aichele and Felbermayr (2015). Once this straigh-forward but time-consuming data exercise is completed, we will be able to include more sectors and account for the full cost of embedded carbon.

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[10] accessible under http://www.oecd.org/sti/ind/input-outputtables.htm

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Appendix: Krugman Model

(omitting sectoral indices)

.1 Consumers

Utility:

$$U_i = H_i^{1-\omega} M_i^{\omega}, \text{ with } M_i = \prod_{s=1}^{S} (M_i^s)^{\mu^s}, M_i^s = \left(\sum_{j=1}^{K} N_j^s (q_{ij}^s)^{\frac{\sigma^s - 1}{\sigma^s}} \right)^{\frac{\sigma^s}{\sigma^s - 1}} \tag{16}$$

Defining:

- $\sigma^s > 1$ sectoral elasticity of substitution
- μ^s expenditure share of sector s with $\sum \mu^s = 1$
- N_j^s number of symmetric varieties produced in country j (endogenous)
- $\tau_{ij}^s \geq 1$ iceberg trading cost

Dual price indexes:

$$\Pi_i = \prod_{s=1}^{S} (P_i^s)^{\mu^s} \tag{17}$$

$$P_i^s = \left(\sum_{j=1}^{K} N_j^s (p_{ij}^s)^{1-\sigma^s} \right)^{1/(1-\sigma^s)} \tag{18}$$

$$p_{ij}^s = \tau_{ij}^s p_j^s \tag{19}$$

.2 Firms

- Normalize wage (and all other cost factors) $w_i = 1$
- minimum unit cost function $c_i^s(t_i, w_i)$ has “usual” properties: homogeneous of degree 1, increasing, strictly convex in all arguments.
- $t_i \geq 1$ are ad valorem carbon tax; no tax: $t_i = 1$
- positive markup justified by fixed entry costs

$$C_i^s = c_i^s(t_i, 1) y_i^s + f^s \tag{20}$$

$$\pi_i^s = (p_i^s - c_i^s(\cdot)) y_i^s - f^s (= 0) \tag{21}$$

$$\text{assume } \frac{\partial P_i^s}{\partial p_j^s} = 0 \tag{22}$$

$$\text{then } \frac{\partial y}{\partial p} = -\sigma \frac{y_i}{p_i} \tag{23}$$

$$\frac{\partial \pi_i^s}{\partial p_i^s} \overset{!}{=} 0 \rightleftarrows p_i^s = c_i^s \frac{\sigma^s}{\sigma^s - 1} (\text{constant markup}) \tag{24}$$

$$\bar{y}_i^s = (\sigma^s - 1) f^s / c_i^s \tag{25}$$

.3 Trade flows

(omitting sectoral indices)

$$Q_{mx} = \mu\omega \left(\frac{\sigma - 1}{\sigma} \right)^{\sigma} N_x \frac{L_m}{P_m} \left(\frac{\tau_{mx} p_x}{P_m} \right)^{-\sigma} \tag{26}$$

- Q_{mx} imports form country x to country m
- L_m/P_m describes m's market capacity
- $\frac{\tau_{mx} p_x}{P_m}$ describes the product's inverse competitivity
- $N_x^s(\frac{\tau_{mx} p_x}{P_m})^{-\sigma}$ describes x's supply capacity

Total production of variety i: zero profit for firms and demand from all countries

$$\bar{y}_i = (\sigma^s - 1) f^s / c_i^s = \mu\omega \sum_{m=1}^{K} \frac{L_m}{P_m} \left(\frac{\tau_{mi} p_i}{P_m} \right)^{-\sigma} \tag{27}$$

.4 Carbon

Shepard's Lemma: demand for input factor=derivative of unit cost function assume Cobb-Douglas: $c_i^s = t^{\beta^s}$

$$\begin{aligned} e_i^s &= \frac{\partial c_i^s}{\partial t_i} && (28) \\ &= \beta^s c_i^s / t_i = \beta^s t_i^{\beta^s - 1} && (29) \\ p_i^s &= \frac{\sigma}{\sigma - 1} c_i^s && (30) \\ &= \frac{\sigma}{\sigma - 1} t_i^{\beta} && (31) \\ \theta_{st} &= \frac{e^s t_d}{p_d^s} = \frac{\beta\sigma}{\sigma - 1} && (32) \end{aligned}$$

$$\begin{aligned} \kappa_{e,m} &= \frac{\partial e_i^s}{\partial t_i} / \frac{e_i^s}{t_i} && (33) \\ &= \beta^s - 1 && (34) \\ \kappa_{e,x} &= 0 && (35) \end{aligned}$$

reformulate market-clearing condition (27) using Cobb-Douglas and expression for e_i (first is Aichele, second is Helene):

$$\begin{aligned} \frac{\sigma f}{\mu\omega t_i^{\beta(1-\sigma)}} &= \sum_{m=1}^{K} \frac{\phi_{mi} L_m}{\sum_{k=1}^{K} \phi_{mk} N_k (t_k)^{\beta(1-\sigma)}} && (36) \\ &= \sum_{m=1}^{K} \frac{\tau_{mi}^{-\sigma} L_m}{\sum_{k=1}^{K} \phi_{mk} N_k (t_k)^{\beta(1-\sigma)}} && (37) \end{aligned}$$

Defining

- $\phi_{ij} = \tau_{ij}^{1-\sigma}$
- Φ KxK matrix of ϕ_{ij}, diagonal is 1
- φ_{ij} is i-jth entry of Φ^{-1} – country's inverse centrality to trading partner j
- $\varphi_j = \sum_{k=1}^{K} \varphi_{jk} (t_k)^{\beta(\sigma-1)}$ – cost-weighted measure of country's inverse centrality to all trading partners

gives us optimal number of varieties in country i:

$$N_i^* = \frac{\mu\omega}{\sigma f} (t_i)^{\beta(\sigma-1)} \sum_{j=1}^{K} \frac{\varphi_{ij} L_j}{\varphi_j} \qquad (38)$$

total number of varieties is endogenous but fixed:

$$\bar{N} = \frac{\mu\omega L}{\sigma f} \tag{39}$$

look at share λ_i of total number of varieties rather than N_i (and share of total labor endowment $\theta_i = L_i/L$):

$$\begin{aligned} \lambda_i &= \frac{N_i}{\bar{N}} \qquad (40) \\ &= (t_i)^{\beta(\sigma-1)} \sum_{j=1}^{K} \frac{\varphi_{ij}\theta_j}{\varphi_j} \qquad (41) \end{aligned}$$

re-express traded quantities in 26 using 30 & 41

$$Q_{mx} = \left(\frac{\sigma-1}{\sigma}\right)^{\sigma+1} \mu\omega L_m \tau_{mx}^{-\sigma} t_x^{-\sigma\beta} \left(\sum_j \phi_{mj}(t_j)^{\beta(1-\sigma)} \frac{\lambda_j}{\lambda_x}\right)^{-1} \tag{42}$$

.5 Two countries

- symmetric trading cost ϕ
- country d has CO2 tax ($t_d > 1$) and country f does not ($t_f = 1$)

$$\Phi = \begin{bmatrix} 1 & \phi \\ \phi & 1 \end{bmatrix} \tag{43}$$

$$\Phi^{-1} = \frac{1}{1-\phi^2} \begin{bmatrix} 1 & -\phi \\ -\phi & 1 \end{bmatrix} \tag{44}$$

Imports d= exports f Q_d:

$$Q_{df} = \left(\frac{\sigma-1}{\sigma}\right)^{\sigma+1} (1-\phi^2)\mu\omega L_d \phi^{(\frac{\sigma}{\sigma-1})} \left((t_d)^{\beta(1-\sigma)} \frac{\lambda_f}{\lambda_d} - \phi\right)^{-1} \tag{45}$$

Imports f= exports d Q_f:

$$Q_{fd} = \left(\frac{\sigma-1}{\sigma}\right)^{\sigma+1} (1-\phi^2)\mu\omega L_f \phi^{(\frac{\sigma}{\sigma-1})} t_d^{-\sigma\beta} \left(\frac{\lambda_f}{\lambda_d} - \phi(t_d)^{\beta(1-\sigma)}\right)^{-1} \tag{46}$$

Domestically consumed production in d:

$$Q_{dd} = \left(\frac{\sigma-1}{\sigma}\right)^{\sigma+1}(1-\phi^2)\mu\omega L_d t_d^{-\sigma\beta}\left((t_d)^{\beta(1-\sigma)} - \phi\frac{\lambda_f}{\lambda_d}\right)^{-1} \tag{47}$$

$$\tag{48}$$

Domestically consumed production in f:

$$Q_{ff} = \left(\frac{\sigma-1}{\sigma}\right)^{\sigma+1}(1-\phi^2)\mu\omega L_f\left(1 - \phi(t_d)^{\beta(1-\sigma)}\frac{\lambda_f}{\lambda_d}\right)^{-1} \tag{49}$$

$$\tag{50}$$

Number of varieties:

$$\begin{align}
\bar{N} &= \frac{\mu\omega L}{\sigma f} \tag{51}\\
\varphi_d &= \varphi_{dd}(t_d)^{\beta(\sigma-1)} + \varphi_{df} \tag{52}\\
&= \frac{(t_d)^{\beta(\sigma-1)} - \phi}{1-\phi^2} \tag{53}\\
\varphi_f &= \varphi_{fd} + \varphi_{ff}(t_d)^{\beta(\sigma-1)} \tag{54}\\
&= \frac{1-\phi(t_d)^{\beta(\sigma-1)}}{1-\phi^2} \tag{55}\\
\lambda_d &= (t_d)^{\beta(\sigma-1)}\left(\varphi_{dd}\theta_d/\varphi_d + \varphi_{df}\theta_f/\varphi_f\right) \tag{56}\\
&= (t_d)^{\beta(\sigma-1)}\left(\frac{\theta_d}{(t_d)^{\beta(\sigma-1)} - \phi} - \frac{\phi(1-\theta_d)}{1-\phi(t_d)^{\beta(\sigma-1)}}\right) \tag{57}\\
&= (t_d)^{\beta(\sigma-1)}\left(\frac{\theta_d + \phi^2\theta_f - \phi(t_d)^{\beta(\sigma-1)}}{((t_d)^{\beta(\sigma-1)} - \phi)(1-\phi(t_d)^{\beta(\sigma-1)})}\right) \tag{58}\\
\lambda_f &= \left(\frac{\theta_f}{1-\phi(t_d)^{\beta(\sigma-1)}} - \frac{\phi\theta_d}{(t_d)^{\beta(\sigma-1)} - \phi}\right) \tag{59}\\
&= \left(\frac{(t_d)^{\beta(\sigma-1)}(\phi^2\theta_d + 1 - \theta_d) - \phi}{((t_d)^{\beta(\sigma-1)} - \phi)(1-\phi(t_d)^{\beta(\sigma-1)})}\right) \tag{60}\\
&= 1 - \lambda_d \tag{61}\\
\frac{\lambda_f}{\lambda_d} &= \frac{1-\lambda_d}{\lambda_d} = \frac{1}{\lambda_d} - 1 \tag{62}
\end{align}$$

$$\tag{63}$$

Total domestic production (over all varieties):

$$
\begin{aligned}
Y_d &= N_d \bar{y}_d \tag{64}\\
&= \lambda_d \bar{N}(\sigma - 1) f t_d^{-\beta} \tag{65}\\
&= \lambda_d \frac{\mu\omega L}{\sigma}(\sigma - 1) t_d^{-\beta} \tag{66}\\
&= \left(\frac{\theta_d}{(t_d)^{\beta(\sigma-1)} - \phi} - \frac{\phi\theta_f}{1 - \phi(t_d)^{\beta(\sigma-1)}} \right) \frac{\mu\omega L}{\sigma}(\sigma - 1) t_d^{(-\beta\sigma)} \tag{67}\\
&= OR \left(\frac{\theta_d}{(t_d)^{\beta(\sigma-1)} - \phi} - \frac{\phi\theta_f}{1 - \phi(t_d)^{\beta(\sigma-1)}} \right) \frac{\mu\omega L}{\sigma}(\sigma - 1) t_d^{\beta(\sigma-2)} \tag{68}\\
&= Q_{dd} + Q_{fd} \tag{69}\\
Y_d &= N_f \bar{y}_f \tag{70}\\
&= \lambda_f \bar{N}(\sigma - 1) f \tag{71}\\
&= Q_{ff} + Q_{df} \tag{72}\\
& \tag{73}
\end{aligned}
$$

.6 Derivatives

$$\frac{\partial e_i^s}{\partial t_i} = \beta(\beta-1)t_i^{\beta-2} \tag{74}$$

$$\kappa_{e,m} = \frac{\partial e_i^s}{\partial t_i} / \frac{e_i^s}{t_i} \tag{75}$$

$$= \beta^s - 1 \tag{76}$$

$$\kappa_{e,x} = 0 \tag{77}$$

$$\frac{\partial \lambda_f}{\partial t_d} = \frac{\varphi_d' \phi \theta_d}{\varphi_d^2} - \frac{\varphi_f' \theta_f}{\varphi_f^2} \tag{78}$$

$$= \phi\beta(\sigma-1)t_d^{\beta(\sigma-1)-1}\left(\frac{\theta_d}{\varphi_d^2} + \frac{\theta_f}{\varphi_f^2}\right) \tag{79}$$

$$> 0 \tag{80}$$

$$\frac{\partial \lambda_d}{\partial t_d} = -\frac{\partial \lambda_f}{\partial t_d} \tag{81}$$

$$< 0 \tag{82}$$

$$\frac{\partial(\lambda_f/\lambda_d)}{\partial t_d} > 0 \tag{83}$$

$$\frac{\partial Q_{fd}}{\partial t_d} = \frac{Q_{fd}}{t_d}\left[-\sigma\beta + \frac{\phi\beta(1-\sigma)(t_d)^{\beta(1-\sigma)} - t_d\frac{\partial(\lambda_f/\lambda_d)}{\partial t_d}}{\frac{\lambda_f}{\lambda_d} - \phi(t_d)^{\beta(1-\sigma)}}\right] \tag{84}$$

$$\frac{\partial Q_{dd}}{\partial t_d} = \frac{Q_{dd}}{t_d}\left[-\sigma\beta + \frac{\beta(\sigma-1)t_d^{\beta(1-\sigma)} + \phi t_d\frac{\partial(\lambda_f/\lambda_d)}{\partial t_d}}{(t_d)^{\beta(1-\sigma)} - \phi\frac{\lambda_f}{\lambda_d}}\right] \tag{85}$$

$$\frac{\partial Q_{df}}{\partial t_d} = \frac{Q_{df}}{t_d}t_d^{\beta(1-\sigma)}\left[\frac{\beta(\sigma-1)\frac{\lambda_f}{\lambda_d} - t_d\frac{\partial(\lambda_f/\lambda_d)}{\partial t_d}}{(t_d)^{\beta(1-\sigma)}\frac{\lambda_f}{\lambda_d} - \phi}\right] \tag{86}$$

$$\frac{\partial Q_{ff}}{\partial t_d} = \frac{Q_{ff}}{t_d}t_d^{\beta(1-\sigma)}\phi\left[\frac{\beta(1-\sigma) - t_d\frac{\partial(\lambda_f/\lambda_d)}{\partial t_d}}{1 - \phi t_d^{\beta(1-\sigma)}\frac{\lambda_f}{\lambda_d}}\right] \tag{87}$$

$$\frac{\partial Y_d}{\partial t_d} = \frac{Y_d}{t_d}\left(\underbrace{-\sigma\beta}_{\text{direct competitive effect}} + \underbrace{\frac{\partial \lambda_d}{\partial t_d}\frac{t_d}{\lambda_d}}_{\text{elasticity of number of varieties},\kappa_{\lambda_d}<0}\right) \tag{88}$$

$$\frac{\partial Y_f}{\partial t_d} = \frac{Y_f}{t_d}\underbrace{\frac{\partial \lambda_f}{\partial t_d}\frac{t_d}{\lambda_f}}_{\text{elasticity of number of varieties},\kappa_{\lambda_f}>0} \tag{89}$$

$$\tag{90}$$

carbon leakage and elasticities, defining $\hat{x} = \partial x / x$:

$$TR^s = \frac{e_f(Q_{df} + Q_{ff})}{e_d(Q_{fd} + Q_{dd})} \tag{91}$$

$$\propto \frac{Q_{df}}{Q_{fd} + Q_{dd}} = \frac{Q_{df}}{Y_d} \tag{92}$$

$$CL = \frac{\partial(e_f(Q_{df} + Q_{ff}))/\partial t_d}{\partial(e_d(Q_{fd} + Q_{dd}))/\partial t_d} \hat{t}_d \tag{93}$$

$$log(TR) = log(e_f) + log(Y_f) - log(e_d) - log(Y_d) \tag{94}$$

$$\approxeq log(\bar{TR}) + \frac{\partial \bar{TR}/\partial t_d}{\bar{TR}} (t_d - \bar{t_d}) \tag{95}$$

$$\hat{TR} = CL = \underbrace{\underbrace{\frac{\partial e_f/\partial t_d}{e_f}}_{=0} \hat{t}_d - \underbrace{\frac{\partial e_d/\partial t_d}{e_d}}_{=\beta>0} \hat{t}_d}_{\text{technique effect}} + \underbrace{\underbrace{\frac{\partial Y_f/\partial t_d}{Y_f}}_{\kappa_{Y_f}>0} \hat{t}_d - \underbrace{\frac{\partial Y_d/\partial t_d}{Y_d}}_{\kappa_{Y_d}<0} \hat{t}_d}_{\text{scale effect}} \tag{96}$$

$$\kappa_{\lambda_f} = \phi\beta(\sigma - 1) t_d^{\beta(\sigma-1)-1} \frac{\theta_d \varphi_f^2 + \theta_f \varphi_d^2}{(\theta_d \varphi_f - \phi\theta_f \varphi_d)\varphi_f \varphi_d} \tag{97}$$

$$\kappa_{\lambda_d} = -\frac{\partial \lambda_f}{\partial t_d} \frac{t_d}{\lambda_d} \tag{98}$$

$$= \phi\beta(1 - \sigma) \frac{\theta_d \varphi_f^2 + \theta_f \varphi_d^2}{(\theta_d \varphi_f - \phi\theta_f \varphi_d)\varphi_f \varphi_d} \tag{99}$$

$$\kappa_{\lambda_f} = -\kappa_{\lambda_d} \frac{\lambda_d}{1 - \lambda_d} \tag{100}$$

$$\kappa_{Y_d} = -\sigma\beta + \kappa_{\lambda_d} \tag{101}$$

$$\kappa_{Y_f} = \kappa_{\lambda_f} \tag{102}$$

$$= -\kappa_{\lambda_d} \frac{\lambda_d}{1 - \lambda_d} \tag{103}$$

$$\kappa_{Y_f} - \kappa_{Y_d} = \kappa_{\lambda_f} + \sigma\beta - \kappa_{\lambda_d} \tag{104}$$

$$= \sigma\beta - \underbrace{\frac{\kappa_{\lambda_d}}{\lambda_d}}_{<0} \tag{105}$$

$$\frac{\kappa_{\lambda_d}}{\lambda_d} = \phi\beta(1 - \sigma) t_d^{\beta(1-\sigma)} \frac{\theta_d \varphi_f^2 + \theta_f \varphi_d^2}{(\theta_d \varphi_f - \phi\theta_f \varphi_d)^2} \tag{106}$$

$$CL = \beta(\sigma - 1)(1 + k)\hat{t} \tag{107}$$

$$\text{with } k := \phi \frac{\theta_d \varphi_f^2 + \theta_f \varphi_d^2}{(\theta_d \varphi_f - \phi\theta_f \varphi_d)^2} \tag{108}$$

$$= (1 + k')\hat{t}\theta \tag{109}$$

Estimation equation:

$$dQ_{df,t}/dY_{d,t} = \alpha + \gamma\theta\hat{t}_{d,t} + \mu_s + \mu_t + \epsilon_{st} \tag{110}$$