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Can the Terms of Trade Externality Outweigh Free-Riding? The Role of Vertical Linkages*

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Abstract

This paper analyzes the role of vertical linkages on the international effects of environmental policy. With vertical linkages, stricter environmental policy at home indirectly reduces pollution in the rest of the world. This spillback effect can reinforce the free-rider problem that arises under strategic interaction. When pollution is transboundary a race to the bottom ensues, despite the fact that vertical linkages make it easier for national regulators to export the costs of environmental policy via the terms of trade. We also find that while trade liberalization can be good for the environment, vertical linkages tend to increase global pollution.

Keywords: Globalization, Trade and Environment, Carbon leakage, Climate Policy, Input-Output.

JEL classification: F18, Q56, Q58.

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1 Introduction

Going back at least to Leontief (1970), scholars have recognized the importance of accounting for inter-industry relationships when tracking the environmental repercussions of economic activities. For at least two reasons, this insight has become increasingly relevant at the global level. For one, international fragmentation of production processes has created a myriad of cross-border inter-industry relationships, with intermediate goods trade growing more rapidly over the last few decades than total trade (WTO, 2008). According to Yeats (2001) intermediate input trade already accounted for roughly thirty percent of world trade in manufacturing goods in 1995[1]. Furthermore, in recent years policymakers have shifted their attention to global environmental problems, such as the control of anthropogenic greenhouse gas emissions. Despite a surge in empirical work in the trade and environment literature that uses input-output (I-O) methods to account for inter-industry dependencies, see e.g., Levinson (2009), Davis et al. (2011) and Aichele and Felbermayr (2012), it remains unclear how the effects of environmental policy will play out in a world where these dependencies, or vertical linkages, have gained importance.

This paper analyzes the role of vertical linkages on the international effects of environmental policy. Here we refer to an intermediate good as being interdependent or interconnected through vertical linkages if the production of that particular intermediate good, say a car, is enabled by the input of other intermediate goods, say steel plates, tires or industrial robots, that are potentially sourced from abroad. We argue that vertical linkages shape the incentives facing national regulators concerned with environmental policy in important ways. For one, vertical linkages increase the (opportunity) cost of domestic environmental policy. Additionally, linkages increase the extent to which the costs of environmental policy are exported to the rest of the world via the terms of trade (ToT). On the other side of the same coin, we find that some of the benefits, i.e., emission cutbacks, are exported as well. The latter implies that in the presence of vertical linkages domestic environmental policy reduces emissions abroad.

We determine what happens to global pollution in a world where producers in different countries are becoming increasingly interconnected via vertical linkages and countries set environmental policies non-cooperatively. The outcome of this non-cooperative game is then compared to the outcome under full cooperation, where countries coordinate their policies so as to maximize global welfare. We find that vertical linkages, whether countries cooperate or not, tend to increase global pollution.

We generalize the production structure of the Armington type model of Acemoglu and Ventura (2002) by adding vertical linkages, trade costs and transboundary pollution from intermediate goods production. Each country produces a unique set of tradable intermediate goods using domestic labor and a produced input, i.e., a CES aggregate of all available intermediates. If the dependence of intermediate goods production on produced inputs increases, vertical linkages are said to become stronger. In this simple general equilibrium model, both trade liberalization and stronger vertical linkages bring about an increase in the degree to which intermediates are produced using imports, a process referred to as vertical specialization (see Hummels et al. (2001) and Yi (2003)).

In the first part of the paper we analyze both the marginal costs and benefits of unilateral environmental policy. Naturally, the results obtained here are required for the normative analysis in the second part of the paper, but they also prove to be interesting in their own right. Of primary interest here are a country's ability to export the costs of environmental policy via changes in the ToT and the sign of pollution leakage, defined as the change in pollution abroad in response to an increase in the stringency of environmental policy at home.

Three findings emerge. First, we show that once countries are mutually dependent on the import of intermediates through vertical linkages, a novel channel for environmental policy opens up. By

[1]For a more thorough overview of empirical studies in the field see Antras and Staiger (2012).

reducing the net supply of intermediate goods to world markets, a stricter domestic environmental policy spills over to the rest of the world where it indirectly reduces output in the import-dependent intermediate goods sector. As in the traditional work on input-output analysis (see Leontief (1970)), the negative global supply effect sets in motion another round of reductions in all countries so that the initial effect is magnified. Second, because of this input-output magnification effect, vertical linkages also increase the opportunity cost of environmental policy. Third, we find that vertical linkages not only raise trade intensity, but also lower the net import elasticity of demand, implying larger ToT effects.

Even though the production and consumption of intermediate goods tend to shift to producers in unregulated countries, this is not sufficient to offset the global supply effect. *The first contribution* of the paper is therefore to explain the occurrence of negative leakage, with pollution in other countries not increasing, but decreasing under unilateral policy. Negative leakage is an interesting and surprising outcome, as most studies have focussed exclusively on the opposite case of positive leakage, see e.g., Babiker (2005).

In the second part of the paper we then apply the comparative static results to study optimal non-cooperative and cooperative environmental policies. Whether strategic interaction between national policymakers leads to levels of pollution that are inefficiently high, depends on the geographic scope of the relevant pollutant and hence on the relative strength of the terms of trade motive and the free riding motive, two externalities that lie at the heart of our normative analysis. As national interests are assumed to be of paramount importance to domestic regulators, they ignore the positive impact of domestic environmental policy on the rest of the world. This incentive, here referred to as free-riding, is reinforced by vertical linkages as regulators fail to take into account that a reduction in pollution abroad also spills back to other countries.

We show that if pollution spillovers are strong, as in the case of greenhouse gas emissions, the incentive to free-ride always overwhelms the ToT motive, countries install relatively weak environmental standards and a race to the bottom ensues. In situations where national policymakers are dealing with pollutants that are local in scope, the dominant terms-of-trade externality invokes stricter standards and a race to the top is obtained instead.

While the ToT externality may thus never outweigh free-riding in the case of transboundary pollution, we do find, however, that linkages can soften the race to the bottom result. This constitutes the paper's *second contribution*. Whether a certain reduction in emissions is realized at home or abroad, becomes irrelevant when the geographic scope of pollutants is global. In that case, the exporting benefits effect does not influence decisionmaking. Stated otherwise, when pollution is transboundary, vertical linkages do not affect the degree of free-riding. With only the enhanced ToT motive left, the non-cooperative policy then partially converges to the cooperative policy when linkages grow stronger.

Finally, as a *third and main contribution* we show that when countries become increasingly interdependent via vertical linkages, the net marginal benefits of pollution grow larger and global pollution tends to increase. This result, relevant for both cooperative and non-cooperative policy, arises from the opportunity cost effect. When production is increasingly reliant on produced inputs, many of which are sourced from all over the world, labor becomes increasingly productive. It is therefore more costly to divert resources away from production towards pollution abatement.

Our main contribution has implications for the relationship between vertical specialization and the environment. Although trade liberalization and input-output linkages both raise the degree of vertical specialization, only trade liberalization can potentially lower pollution. Whether vertical specialization is thus good or bad for the environment depends crucially on whether its expansion is driven by stronger vertical linkages or by trade liberalization.

This paper relates to a number of strands in the literature. In the literature on trade and the environment the environmental consequences of trade in intermediate goods are relatively unexplored. Some important exceptions are Benarroch and Weder (2006), McAusland (2004) and Hamilton and Requate (2004). None of these studies, however, study the relationship between vertical linkages and environmental policy in a multi-country general equilibrium model.

Our work is also related to a concern that globalization will intensify regulatory competition in national environmental policies, thereby provoking a race to the bottom with negative consequences for global environmental quality (see Ederington (2010)). As we have argued, this does not represent a necessary outcome, because ToT effects could induce a race to the top instead. Using trade flow data for the US and Canada, McAusland and Millimet (2013) find robust evidence that international trade, but not intranational trade, exerts a beneficial effect on environmental quality, a result that is consistent with the ToT channel[2]. Markusen (2013) is another study emphasizing that the costs of environmental policy can be exported via the ToT, but he does not consider the role of vertical linkages, nor is he concerned with the feasibility of negative leakage.

Last but not least, a small number of papers has explored the possibility of negative leakage in analytically tractable trade models. Using a two-sector model with three factors of production, Karp (2013) shows that unilateral regulation lowers national income, reduces demand for both clean and dirty goods and shifts domestic production factors into home's dirty goods sector. This factor mobility effect obviates the need for dirty goods supply abroad, thereby promoting negative leakage. Fullerton et al. (2014) show that negative leakage can result from a so-called abatement resource effect; by increasing its demand for the internationally mobile factor of production, the regulated sector in the policy active country crowds out production in the unregulated sector abroad.

Similar to Fullerton et al. (2014) and Karp (2013), we use a tractable trade model to highlight a channel for negative leakage. Whereas in these papers the (international) mobility of production factors is key, in our contribution the potential for negative leakage is rooted in the tradability of differentiated produced inputs. The scope of our analysis is broader than these papers as they do not consider strategic interaction. We examine the role of labor mobility in an extension section where we construct a two-sector Eaton and Kortum (2002) model with vertical linkages. We use this model to explain how the linkages based channel compares to the factor mobility channel for negative leakage.

The rest of this paper is set up as follows. In the next section, we discuss the model's assumptions and characterize the equilibrium, paying special attention to the impact of vertical linkages. Section 3 forms the core of our analysis. Here we study both the marginal cost and marginal benefits of a unilateral marginal change in environmental policy. We also explain how negative leakage can arise in a setting with vertical linkages and perform some numerical analysis to assess its sensitivity. In section 4 we study a cooperative and non-cooperative approach to environmental policy, compare their outcomes in terms of global emission levels and analyze the role of vertical linkages. Section 5 extends our analysis to a Ricardian model of trade. The last section concludes. All proofs are in the appendix.

2 The Model

We adopt the production structure of the Armington type model of Acemoglu and Ventura (2002) and enrich it by adding trade costs, vertical linkages and (transboundary) pollution from the production of intermediate goods. The world economy consists of a (large) number of N countries indexed by j. There is one primary factor of production, labor L_j, that is supplied inelastically and immobile between countries. The size of the world population equals $L^w \equiv \sum_{j=1}^{j=N} L_j$. In each country there are three sectors, producing (1) tradable intermediate goods, (2) a composite intermediate good and (3) a non-

[2]Broda, Limao and Weinstein (2008) provide strong empirical evidence for terms of trade considerations playing an active role in the formation of trade policy. Consistent with the theory on optimal tariffs, they find that non-WTO members systematically set higher tariffs on imports that are supplied inelastically.

tradable final consumption good. The set of tradable intermediate goods contains a total number of m varieties. Each country produces a unique subset n_j from this set of varieties with $\sum_{j=1}^{j=N} n_j = m$. Countries engage in costly trade in intermediate goods in order to produce the composite intermediate good. To sell one unit of an intermediate good in another country a producer must ship $t \geq 1$ units, which implies that $t-1$ units melt in transit. The composite intermediate good is used in the production of the consumption good, but also serves as an input to the production of tradable intermediates (input-output), as in Eaton and Kortum (2002), Alvarez and Lucas (2007) and Ramondo and Rodriguez-Clare (2013).

2.1 Welfare, Consumption and Pollution

Per capita welfare v_j in country j depends positively on per capita consumption $c_j \equiv C_j/L$ and negatively on damages from (transboundary) pollution Z_j:

$$v_j = \log c_j - \eta Z_j \tag{1}$$

where η represents the marginal damage from pollution. Let z_j denote emissions generated in the production of one variety of the intermediate good in country j. Then total pollution experienced by country j is given by

$$Z_j = n_j z_j + \sum_{i \neq j} \zeta n_i z_i$$

where the parameter ζ indicates the extent to which pollution disperses geographically: when $\zeta = 0$, pollution is a local public bad (e.g., sulfur dioxide), while when $\zeta = 1$ the pollutant represents a global public bad (e.g., carbon dioxide).

2.2 Production of Intermediate Goods and Final Goods

The production of intermediate goods requires the input of labor and the composite intermediate good, i.e., the produced input. In turn, production of the composite intermediate good requires the input of all available intermediate goods varieties. From this it follows immediately that the production of each variety is vertically linked to the production of all the other varieties. Production of the intermediate good y_j and the composite intermediate good X_j in country j are both characterized by constant returns to scale:

$$y_j = g_j(1-\theta_j)\left(\frac{L_{jy}}{\beta}\right)^{\beta}\left(\frac{X_{jy}}{1-\beta}\right)^{1-\beta} \tag{2}$$

$$X_j = \left(\sum_{i=1}^{N} n_i y_{ij}^{\frac{\varepsilon-1}{\varepsilon}}\right)^{\frac{\varepsilon}{\varepsilon-1}} \quad , \quad \varepsilon > 1 \tag{3}$$

where y_{ij}, X_{jy}, L_{jy}, g_j and $\varepsilon > 1$ represent respectively consumption (or import) of a typical intermediate good from country i by country j, inputs of the composite intermediate good and labor in the intermediate goods sector, total factor productivity (TFP) in the intermediate goods sector and the elasticity of substitution between intermediates. Naturally, a marginal increase of the expenditure share $1-\beta$ can be interpreted as a marginal increase of the strength of vertical linkages in the economy.

The production of one net unit of output of the intermediate good generates $e(\theta_j)$ units of pollution, where θ_j is the fraction of gross output of the intermediate good used for abatement in country j. Following Copeland and Taylor (2003) we assume a simple iso-elastic specification, $e(\theta_j) = (1-\theta_j)^{\frac{1-\alpha}{\alpha}}$

with $0 < \alpha < 1$. Total emissions z_j of a typical variety then equal:

$$z_j = e(\theta_j)y_j \tag{4}$$

The non-tradable final consumption good C_j is produced with the input of the composite intermediate good X_{jC} and labor L_{jC}:

$$C_j = \left(\frac{L_{jC}}{1-\tau}\right)^{1-\tau}\left(\frac{X_{jC}}{\tau}\right)^{\tau} \tag{5}$$

2.3 Market Equilibrium

2.3.1 Equilibrium Wages

Markets for intermediate goods, the composite intermediate good and the consumption good are subject to perfect competition, and therefore unit cost pricing prevails:

$$p_j = \frac{1}{g_j}\frac{1}{1-\theta_j}{w_j}^{\beta}P_j^{1-\beta} \tag{6}$$

$$P_j = \left[n_j p_j^{1-\varepsilon} + \sum_{i\neq j} n_i \phi {p_i}^{1-\varepsilon}\right]^{\frac{1}{1-\varepsilon}} \tag{7}$$

$$p_{jC} = {w_j}^{1-\tau}P_j^{\tau} \tag{8}$$

where p_j is the intermediate goods price, P_j is the price of the composite intermediate good, w_j represents the domestic wage rate and $\phi \equiv t^{1-\varepsilon} \leq 1$ is a parameter measuring the 'freeness' of trade. Market clearing for the composite intermediate good in each country requires $X_j = X_{jC} + n_j X_{jy}$. Likewise, in equilibrium the sum of labor employed in the production of tradable intermediates and the final consumption good should equal the supply of labor, $L_j = L_{jC} + n_j L_{jy}$.

Next, demand by country i for a typical intermediate produced in country j is of the constant elasticity form, $y_{ji} = \phi_{ji} p_j^{-\varepsilon} P_i^{\varepsilon-1} E_i$, where E_i equals nominal expenditures on intermediates by country i. Define nominal income in country j as $I_j = w_j L_j$. From profit maximization in the intermediate goods sector and the final consumption goods sector and labor market clearing it follows that $E_j = \frac{\tau}{\beta} I_j$, such that global demand for a typical variety can be written as

$$y_j = \sum_i y_{ji} = p_j^{-\varepsilon} P_j^{\varepsilon-1}\frac{\tau}{\beta} I_j + \sum_{i\neq j} \phi p_j^{-\varepsilon} P_i^{\varepsilon-1}\frac{\tau}{\beta} I_i \tag{9}$$

Next, define world income and relative income as $I^w \equiv \sum_{j=1}^{j=N} I_j$ and $\lambda_j \equiv \frac{I_j}{I^w}$ respectively. The balanced trade condition can then be obtained by equating the supply of and demand for country j's intermediate goods (see appendix A for a more detailed derivation):

$$I_j = n_j {p_j}^{1-\varepsilon}\Gamma_j I^w \tag{10}$$

where $\Gamma_j \equiv P_j^{\varepsilon-1}\lambda_j + \sum_{i\neq j} \phi P_i^{\varepsilon-1}\lambda_i$. In equilibrium, a country's relative level of income is equal to $n_j {p_j}^{1-\varepsilon}\Gamma_j$, which represents the world income expenditure share on commodities from that country. When trade is costly $\Gamma_j \neq 1$ and producers will sell more in markets where the cost of living is high, trade barriers are low and relative income is high.

Next, for comparative statics purposes we will concern ourselves only with a version of the model that differentiates between two "groups" of countries, group A and group B. Group A consists of only one country, to which we will refer as country A, which unilaterally adjusts its environmental policy.

Group B consists of $N-1$ passive countries. We assume that all countries within group B are fully symmetric, but we do allow for differences in population size and technology between country A on the one hand and countries from group B on the other hand.

The general equilibrium of the model can be represented by the wage rate in country A (w_A) and the wage rate in group B (w_B). Taking P_A as the numeraire price, using the price index equations (7) for country A and group B to write P_B as a function of w_A only, and substituting for intermediate goods prices and $P_B\left(w_A\right)$ into country A's price index equation (7) and balanced trade equation (10), the equilibrium pair (w_A^*, w_B^*) then solves the following set of equations (see the appendix):

$$1 = n_A\left(\frac{1}{g_A}\frac{1}{1-\theta_A}w_A^{\beta}\right)^{1-\varepsilon} + \phi\left(N-1\right)n_B\left(\frac{1}{g_B}\frac{1}{1-\theta_B}w_B{}^{\beta}\left(P_B\left(w_A\right)\right)^{1-\beta}\right)^{1-\varepsilon} \tag{11}$$

$$w_A L_A = n_A\left(\frac{1}{g_A}\frac{1}{1-\theta_A}w_A^{\beta}\right)^{1-\varepsilon}\left[w_A L_A + \phi\left(N-1\right)\left(P_B\left(w_A\right)\right)^{\varepsilon-1}w_B L_B\right] \tag{12}$$

As we show in the appendix, a unique, asymmetric equilibrium exists and in all countries real income $\frac{w_j}{P_j}$ is higher under trade than under autarky. A closed-form solution to the pair (w_A^*, w_B^*) is available when (a) countries are symmetric or (b) when trade is free. In case (a) it is also straightforward to show that trade liberalization and vertical linkages increase real income and that they are mutually reinforcing. The latter finding is closely related to the notion that linkages can magnify the trade response to tariff reductions, an idea first put forward by Yi (2003).

2.3.2 Equilibrium Pollution

Using profit maximization in the intermediate goods and final goods sectors, the labour market clearing condition and the income constraint we can derive consumption of the composite intermediate as a function of real income, $X_{jy} = \frac{1-\beta}{\beta}\frac{\tau I_j}{n_j P_j}$. Substituting this result into (4) gives the equilibrium level of emissions,

$$z_j = \frac{1}{\beta}e(\theta_j)g_j\left(1-\theta_j\right)\left(\frac{w_j}{P_j}\right)^{1-\beta}\frac{\tau L_j}{n_j} \quad , \quad j = A, B \tag{13}$$

It is also useful to focus on the supply side and write (13) in terms of quantities. In the appendix we show that real income is directly proportional to production of the composite intermediate good:

$$\frac{w_j}{P_j}\frac{\tau L_j}{n_j} = \frac{\lambda_j}{n_j}G_j^{\frac{1}{\beta}} \quad , \quad G_j = G_j\left(\theta_A, \theta_B\right) \quad , \quad j = A, B \tag{14}$$

Via the composite supply term G_j, which is influenced by global environmental policies, a stricter domestic environmental standard spills over to other countries. The latter channel only arises with vertical linkages ($\beta < 1$).

3 The Effects of Unilateral Environmental Policy

We analyze the effects of a unilateral marginal change in country A's environmental policy on real wages and pollution. Policy makers in group B are assumed to be passive. The government is able to indirectly control the intensity of abatement θ_j by imposing an environmental standard (or emission standard) $s_j = e(\theta_j)$, where θ_j is uniquely determined by $\theta_j = e^{-1}(s_j)$. In the remaining of this paper we will always refer to θ_j when discussing the stringency of environmental policy in country j.

Next, we define the elasticity of variable x with respect to variable y as $\epsilon_y^x \equiv \frac{dx/x}{dy/y}$. To simplify notation, we use a slightly altered definition in case $y = \theta_A$, that is, $\epsilon^x \equiv \frac{dx/x}{d\theta_A/(1-\theta_A)}$. In addition, let us define net imports as $nIM_j \equiv I_j - n_j p_j^{1-\varepsilon}\Gamma_j I^w$ and let us refer to $a \equiv \frac{1}{\beta}\frac{dp_A/p_A}{d\theta_A/(1-\theta_A)} = \frac{\frac{\tau}{\beta}\left(1-\frac{\lambda_A}{\Gamma_A}\right)}{\epsilon^{nIM}_{w_A}} > 0$ and $b \equiv \left(\frac{dw_A/w_A}{d\theta_A/(1-\theta_A)}\right)_{dp_A=0} = \frac{1}{\beta} > 0$ respectively as the environmental policy elasticity of country A's wage rate, in as far changes in the environmental standard affect country A's terms of trade (ToT effect), and the environmental policy elasticity of country A's wage rate at constant prices (TFP effect).

Proposition 1. Unilateral Environmental Policy.
Consider a unilateral marginal increase in the stringency of environmental policy by country A. In all countries:
(i) *the real wage falls,*

$$\epsilon^{w_A/P_A} = a - b < 0 \tag{15}$$

$$\epsilon^{w_B/P_B} = \left(\underbrace{-a\epsilon^{w_B}_{p_A}}_{<0}\underbrace{-\epsilon^{P_B}}_{>0}\right) < 0 \tag{16}$$

and prices of intermediate goods increase at home and decrease abroad, $\epsilon^{p_A} = \beta a > 0$ and $\epsilon^{p_B} < 0$.
(ii) *pollution is reduced,*

$$\epsilon^{z_A} = -\frac{1}{\alpha} + (1-\beta)\,\epsilon^{w_A/P_A} < 0 \tag{17}$$

$$\epsilon^{z_B} = (1-\beta)\,\epsilon^{w_B/P_B} < 0 \tag{18}$$

Example 1. *Free trade. In this case* $a := \frac{1}{\beta}\frac{1-\lambda_A}{1+\beta(\varepsilon-1)}$, $z_j := \frac{1}{\beta}e(\theta_j)g_j\left(1-\theta_j\right)\left(\frac{\lambda_j}{n_j}G^{\frac{1}{\beta}}\right)^{1-\beta}\left(\frac{\tau L_j}{n_j}\right)^{\beta}$ *and* $\epsilon^{z_B} := -\left(1-\beta\right)\frac{\lambda_A}{1-\lambda_A}a < 0$.

Lemma 1. *Symmetric countries. If trade costs are sufficiently small, stronger vertical linkages will increase the ToT coefficient,* $\frac{da}{d(1-\beta)} > 0$. *A sufficient condition reads* $\phi > \frac{1}{2}\frac{N-2}{N-1}$.

The Effects on Real Wages
Environmental policy affects the real wage rate via two different channels. First, there is a TFP or opportunity cost effect. Since the net unit labor requirement increases with the stringency of environmental policy, the return to labor must go down. Second, product differentiation implies that a part of the costs of environmental policy can be exported via higher prices. A relatively wealthy country consumes a non-negligible portion $\frac{\lambda_A}{\Gamma_A}$ of domestically produced dirty intermediates. This 'burden' lowers export intensity, $\frac{\tau}{\beta}\left(1-\frac{\lambda_A}{\Gamma_A}\right)$, and reduces the ToT effect. Stated otherwise, when the number of countries is large, domestic producers of intermediate goods will ceteris paribus depend heavily on imported inputs, the more so if vertical linkages are strong, and are therefore less affected by domestic regulation[3]. The net impact of environmental policy on the domestic real wage rate is unambiguously negative, because the positive ToT effect is always overwhelmed by the negative TFP effect.

Vertical linkages influence the costs of environmental policy in a number of ways. First of all, vertical linkages increase the dependence of exports on foreign inputs. In particular, the 'degree of specialization' increases, $\frac{1}{\varepsilon} < \frac{1}{\varepsilon-(1-\beta)(\varepsilon-1)} = \frac{1}{1+\beta(\varepsilon-1)}$, making it more difficult for producers to substitute away

[3]The finding that terms of trade effects are larger in a setting with a large number of countries would arise in any model with differentiated products. Employing the monopolistic competition model of Krugman (1980), McAusland and Millimet (2013) explain how a high trade intensity enables regulators to export the costs of environmental policy to *consumers* abroad, an effect they coin 'regulatory decoupling'. With vertical linkages, costs of environmental regulation are shifted to *producers* abroad, the more so if linkages are strong.

towards other (local) inputs. Therefore the ToT effect becomes larger. Second, the introduction of I-O linkages gives rise to an intermediate goods multiplier $\frac{1}{\beta}$ that increases the magnitude of both the TFP effect and ToT effect. Intuitively, a higher standard in country A diminishes production of intermediate goods in that country. In turn, this fall in supply then also lowers production of intermediate goods in other countries, which then feeds back into country A etc. This cycle will repeat itself again and again, culminating in the geometric sequence, $1 + (1-\beta) + (1-\beta)^2 + .. = \frac{1}{1-(1-\beta)} = \frac{1}{\beta} \geq 1$. Thus, via this multiplier effect vertical linkages tend to raise the opportunity cost of environmental policy[4].

Third, vertical linkages also interact with trade cost induced effects. To get a grasp of this, note first that, in response to stricter environmental policy in country A, world expenditures will shift to intermediates produced in group B, such that Γ_A falls. This expenditure shifting effect operates through both the export intensity term (the numerator of a) and the net import elasticity of demand term, $\epsilon^{nIM}_{w_A}$ (the denominator of a). In addition, production losses due to trade frictions are exacerbated (production inefficiency effect)[5]. One can show analytically, provided countries are symmetric and trade costs sufficiently small, that vertical linkages tend to weaken the expenditure shifting effect and production inefficiency effect, thereby strengthening the ToT effect.

The Effects on Pollution

Stricter policy in country A reduces pollution via three effects. First, with relative income of country A falling while that of group B increasing ($\lambda_A \downarrow$, $\lambda_B \uparrow$), the 'consumption' and production of intermediates decreases in country A and increases in group B. This income or allocation effect tends to reduce pollution in country A while increasing pollution in group B. Second, stricter policies in country A reduce the supply of intermediates to domestic and world markets ($G \downarrow$). Imports by group B fall and ceteris paribus output in group B must decrease. This negative production or supply effect thus reduces pollution in both country A and group B. Intermediate goods, like physical capital, represent produced inputs, and by limiting supply of these inputs, domestic environmental policy reduces pollution abroad[6]. If pollution is transboundary, this effect will spill back to country A in the form of reduced pollution damages.

Third, when trade costs are positive the allocation effect in country B is reinforced by expenditure shifting. The magnitude of the ToT coefficient a diminishes and pollution in group B tends to increase. Stated otherwise, with the price of country A's intermediate goods increasing, producers will shift expenditures towards intermediates produced in group B countries. Due to these backward linkages, the 'consumption' and production of intermediates in group B all increase in response to a stricter policy in country A, and there is more intra-group trade. In equilibrium the price index P_B falls relative to P_A and income in country A falls further relative to income in country B. The overall impact of these three effects is a reduction of pollution in both country A and country B. In the latter, the negative supply effect overwhelms the positive allocation and expenditure shifting effects. From (18) we observe that pollution in group B is unaffected in the absence of vertical linkages.

[4]Using the 2006 edition of the OECD I-O database, Jones (2013) concludes that for most countries "one over one minus the (average) intermediate goods share" represents a simple yet good approximation to the true multiplier.

[5]Note that under extreme parameter values (very low β and ϕ) the sign of the expenditure shifting effect could be reversed and the production inefficiency effect could become so large, that the terms of trade effect turns negative. We discard this possibility.

[6]On a technical level, our results bear a resemblance to Harstad (2012). In a recent, influential study Harstad (2012) has shown that supply side policies are key in overcoming free riding. Once countries can trade the rights to exploit fossil fuel deposits, a climate coalition's best policy is simply to buy foreign deposits. The coalition would then restrict domestic supply by using e.g., a production tax. Although the coalition's policies raise the price of fossil fuels on world markets, they do not result in supply side leakage. This surprising effect occurs because the foreign fossil fuel supply curve has become locally inelastic after the coalition has acquired the marginal foreign deposits. In fact, higher prices now reduce fossil fuel consumption in other countries as well. Hence, leakage becomes negative. In this paper, technological heterogeneity implies that the supply of each variety is locally elastic but globally inelastic. Hence, when stricter environmental policy reduces the domestic supply of intermediates to world markets, consumption of these intermediates by intermediate goods producers in all other countries will fall, thereby inducing negative leakage.

To provide some further guidance to the sensitivity of the leakage rate with respect to key parameters, let us denote the rate of leakage as a function of the standard θ_A by $\frac{\Delta Z_B}{Z_B} = \frac{Z_{B,0}-Z_{B,1}}{Z_{B,0}}$, such that positive values correspond to negative leakage. We then consider the following numerical example:

Numerical Example 1. Baseline parameter values are $N = 2$, $n_A = n_B = 1$, $g_A = g_B = 2$, $\tau = 0.8$, $\beta = 0.5$, $L_A = L_B = 1$ and $\theta_B = 0$. The left and right panel of figure 1 depict leakage rates for different levels of the elasticity of substitution (with $\phi = 0.9$) and different levels of trade costs (with $\varepsilon = 3$) respectively. A higher elasticity of substitution and higher trade costs are shown to reduce the magnitude of negative leakage.

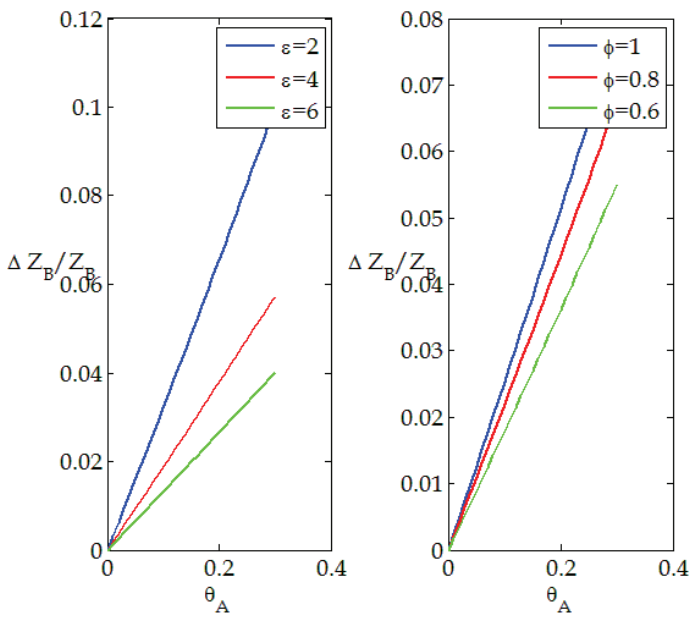

Figure 1. Sensitivity of Leakage rates.

As far as we know, Fullerton et al. (2014) and Karp (2013) are the only other papers that present a mechanism for negative leakage using a 'conventional' trade model. Similar to Fullerton et al. (2014) we do not claim that leakage actually is negative. Our results merely illustrate that conventional models might have overlooked certain channels. Interestingly, the mechanism for negative leakage presented here is purely market driven and different from mechanisms that rely on strategic interaction and income effects, as in Copeland and Taylor (2005).

4 Cooperative and Non-Cooperative Environmental Policy in the Global Economy

In this section we conduct a normative analysis of environmental policy in a world with vertical linkages. Here it is assumed that the world consists of a large number of symmetric countries while trade is costly. We consider respectively a cooperative and non-cooperative approach to environmental policy, which we will define formally in the next section, and contrast their outcomes in terms of global pollution. In the symmetric Nash equilibrium of the non-cooperative game, a number of externalities distort the non-cooperative standard relative to the cooperative solution. Let us first briefly discuss these externalities, with an emphasis on the role played by vertical linkages, before continuing with our analysis.

First of all, when a stricter environmental standard reduces the emission of pollutants at home, domestic policymakers only internalize these benefits in as much they lower domestic but not foreign pollution damages. This is the conventional free-riding incentive. Once vertical linkages are introduced, stricter environmental policy at home also decreases pollution in the rest of the world (see Proposition 1), which not only lowers pollution damages abroad but potentially at home as well. We can think of this additional effect as a spillback effect, similar to Ogawa and Wildasin (2009). Without cooperation only a certain portion of the spillback effect is internalized. Hence, we may refer to the uninternalized fraction of the spillback effect as a spillback externality. In section 4.2 we will show that this spillback externality magnifies the free-riding incentive if pollution is local, but not if pollution spillovers are global in scope. Thus, depending on the geographic scope of the pollutant, vertical linkage can reinforce the problem of free-riding.

Second, domestic policymakers ignore the negative ramifications of higher prices induced by their environmental policies for intermediate good producers and final good producers in other countries. This ToT externality tends to lead to too little pollution. From Lemma 1 we know that, provided trade costs are not too large, input-output linkages magnify this externality too, irrespective of the type of pollutant.

4.1 Cooperative and Non-Cooperative Environmental Policy

Let us define global welfare by $V^w \equiv \sum_{j=1}^{N} v_j$. Substitution of (1), $c_j = \left(\frac{w_j}{P_j}\right)^\tau$ and (13) into V^w gives

$$V^w = \sum_{i=1}^{N} \log\left(\frac{w_i}{P_i}\right)^\tau - \eta \sum_{i=1}^{N} Z_i \tag{19}$$

Similar to before, we define the elasticity of variable x with respect to θ_j as $\epsilon^x \equiv \frac{dx/x}{d\theta_j/(1-\theta_j)}$ for all x. Under cooperation countries maximize their joint welfare (19). Each country selects a standard θ_j that equates the social marginal cost of the environmental standard, $\Omega_S^C \frac{1}{1-\theta_j}$, to the social marginal benefit of the standard, $\Omega^B \frac{\eta n z_j}{1-\theta_j} + (N-1)\,\Omega_f^B \frac{\eta n z_i}{1-\theta_j}$:

$$\underbrace{-\tau\left[\epsilon^{w_j/P_j} + (N-1)\left(\epsilon^{w_i/P_i}\right)\right]\frac{1}{1-\theta_j}}_{\equiv \Omega_S^C \frac{1}{1-\theta_j}} = \underbrace{-\eta n\left(\begin{array}{c}\left(\epsilon^{z_j} + \zeta\,(N-1)\,\epsilon^{z_i}\frac{z_i}{z_j}\right)\frac{z_j}{1-\theta_j} \\ +(N-1)\left(\epsilon^{z_i} + \zeta\epsilon^{z_j}\frac{z_j}{z_i} + \zeta\,(N-2)\,\epsilon^{z_i}\right)\frac{z_i}{1-\theta_j}\end{array}\right)}_{\equiv \Omega^B \frac{\eta n z_j}{1-\theta_j} + (N-1)\Omega_f^B \frac{\eta n z_i}{1-\theta_j}} \tag{20}$$

A higher standard reduces real income at home and abroad, thereby reducing consumption and utility in all countries. The social marginal benefit of setting a higher standard in country j is a reduction in pollution damages both at home (Ω^B) and in the rest of the world (Ω_f^B), where f is a mnemonic for "foreign" or "free-riding". In each country pollution damages fall because emissions are reduced not only domestically, but also abroad (spillback effects). Before we present the full solution of the optimal cooperative standard θ_C^*, we analyze the non-cooperative problem.

In the non-cooperative game the problem of country j is to maximize $v_j = \log\left(\frac{w_j}{P_j}\right)^\tau - \eta Z_j$ with respect to θ_j, taking the standards set by other countries as given. The first-order condition reads:

$$\underbrace{-\tau\epsilon^{w_j/P_j}\frac{1}{1-\theta_j}}_{\equiv\Omega^C\frac{1}{1-\theta_j}} = \underbrace{-\eta n\left(\epsilon^{z_j}+\zeta\left(N-1\right)\epsilon^{z_i}\frac{z_i}{z_j}\right)\frac{z_j}{1-\theta_j}}_{\equiv\Omega^B\frac{\eta n z_j}{1-\theta_j}} \tag{21}$$

for all $j = 1, .., N$. Each country sets the private marginal cost of meeting the domestic standard (left-hand side term) equal to the private marginal benefit of meeting the domestic standard (right-hand side term) when determining its optimal policy. Equation (21) implicitly determines the best response of country j as a function of the standards set in other countries, $\theta_j^* = BR_j(\theta_{-j})$. Since we have assumed all countries to be identical in terms of endowments, technology and preferences, a symmetric Nash equilibrium exists where each country sets the optimal non-cooperative standard θ_{NC}^*.

4.2 Environmental Policy in Equilibrium

To obtain the equilibrium environmental policies, note first that under full symmetry we can use (11) and (13) to obtain respectively

$$w = \left[\overline{w}\left(1-\theta\right)\right]^{\frac{1}{\beta}} \quad , \quad \overline{w} \equiv g\left[n\left(1+\phi\left(N-1\right)\right)\right]^{\frac{1}{\varepsilon-1}} \tag{22}$$

and

$$z = \bar{z}(1-\theta)^{\Phi} \quad , \quad \bar{z} \equiv \frac{1}{\beta}g\left(\overline{w}\right)^{\frac{1-\beta}{\beta}} L_y \tag{23}$$

where $\bar{z}$ ($\overline{w}$) is the maximum pollution (wage) level in a world without environmental policy and $\Phi \equiv \frac{1}{\alpha} + (1-\beta)\, b$ is the policy elasticity of pollution. Next, we substitute for the real wage and pollution elasticities from Proposition 1 into (20) and (21). After applying symmetry to (20)-(21), we note that all these elasticities, as subsumed under the aggregate marginal cost and marginal benefit elasticities, i.e., the Ω-terms, can be fully written as functions of the TFP effect b and the ToT effect a. Finally, by substituting for $\bar{z}$ from (22)-(23) we obtain closed-form solutions for θ_C^* and θ_{NC}^*:

$$\theta_{NC}^* = 1-\left[\frac{1}{\eta n\bar{z}}\frac{\Omega^C}{\Omega^B}\right]^{\frac{1}{\Phi}} \quad , \quad \theta_C^* = 1-\left[\frac{1}{\eta n\bar{z}}\frac{\Omega_S^C}{\Omega^B+\left(N-1\right)\Omega_f^B}\right]^{\frac{1}{\Phi}} \tag{24}$$

Next, let us refer to a "race to the top" and a "race to the bottom" as situations in which $\theta_{NC}^* > \theta_C^*$ and $\theta_{NC}^* < \theta_C^*$ hold respectively. Define $\bar{\zeta}$ as the spillover coefficient for which $\theta_{NC}^* = \theta_C^*$. Furthermore, to fully characterize the relationship between vertical linkages and the equilibrium policies in (24), let us make two mild assumptions.

Assumption 1. (a) $\overline{w}\left[\frac{1}{\eta n\bar{z}}\frac{\Omega_S^C}{\Omega^B+(N-1)\Omega_f^B}\right]^{\frac{1}{\Phi}} > 1$. (b) $\overline{w}\left[\frac{1}{\eta n\bar{z}}\frac{\Omega^C}{\Omega^B}\right]^{\frac{1}{\Phi}} > 1$.

Furthermore, trade costs are sufficiently low such that vertical linkages increase the ToT effect, as in Lemma 1.

Proposition 2. Environmental Standards: Race to the Bottom or Race to the Top? The Role of Vertical Linkages.
(i) *There exists a unique $\bar{\zeta}$, such that that there is a race to the top for $\zeta < \bar{\zeta}$ and a race to the bottom for $\zeta > \bar{\zeta}$,* provided $\bar{\zeta} \in (0,1)$.

(ii) *When pollution is fully transboundary* ($\zeta = 1$) *there is always a race to the bottom, that is,* $\theta^*_{NC} < \theta^*_C$. *Under A1-a and* $\phi > \frac{1}{2}\frac{N-2}{N-1}$, *stronger vertical linkages increase both the cooperative and non-cooperative standard and diminish the gap between the cooperative and non-cooperative standard,* $\frac{d}{d(1-\beta)}\left(\frac{\theta^*_{NC}}{\theta^*_C}\right) > 0$.
(iii) *Under purely local pollution* ($\zeta = 0$) *there is always a race to the top, that is,* $\theta^*_{NC} > \theta^*_C$. *Under A1-b and* $\phi > \frac{1}{2}\frac{N-2}{N-1}$, *stronger vertical linkages increase both the cooperative and non-cooperative standard, but have an ambiguous impact on the gap between the cooperative and non-cooperative standard,* $\frac{d}{d(1-\beta)}\left(\frac{\theta^*_{NC}}{\theta^*_C}\right) \gtrless 0$.

Example 2. *Free trade and transboundary pollution. In this case, countries internalize a smaller fraction of the social marginal benefits* ($\frac{1}{N}$) *than the social marginal costs of environmental policy* ($1 - \frac{N-1}{N}\frac{1}{1+\beta(\varepsilon-1)}$). *Hence,* $\theta^*_{NC} < \theta^*_C$.

National regulators disregard any benefits from their domestic environmental policies that accrue to other countries. Based on this free-riding motive alone, the non-cooperative standard tends to be smaller than the cooperative standard. At the same time, in a world with a large number of countries, and hence a large number of sovereign governments and international borders, domestic producers of intermediate goods depend heavily on imported inputs, the more so if vertical linkages are strong, and are therefore less affected by domestic regulation (see Proposition 1). This enables national regulators to set a stricter environmental policy than they could under cooperation. Due to this ToT motive the non-cooperative standard actually tends to be larger than the cooperative standard.

Taken together, when the ToT externality overwhelms the free-riding externality the outcome represents a race to the top and otherwise we end up with a race to the bottom. To clarify this trade-off further, consider first the case of transboundary pollutants under free trade. As we show very vividly in example 3, national policymakers underestimate both the global marginal benefits and costs of domestic environmental policy, but the underestimation of the global marginal benefits is always larger. Stated otherwise, the free-riding motive outweighs the ToT externality. Hence, a race to the bottom ensues[7]. For local pollutants it is found that the ToT externality is dominant and a race to the top is obtained instead.

Proposition 2 also explains how linkages affect the non-cooperative standard relative to the cooperative standard. To do this, we first establish how linkages affect the stringency of environmental policy. Under two mild assumptions, the overall relationship between vertical linkages and the environmental standard is always positive. This happens because linkages, among other reasons, increase the scale of pollution ($\bar{z} \uparrow$) and raise the elasticity of global pollution ($\Phi \uparrow$), inducing a stricter environmental standard. This result holds irrespective of the type of pollutant (local vs. global) and the type of policy arrangement (non-cooperative vs. cooperative).

Interestingly, we show that linkages raise the relative non-cooperative standard when pollution is transboundary. In that sense, linkages mitigate the race to the bottom phenomenon. The reasoning is as follows. Keeping the stringency of environmental policy fixed, linkages ensure that a larger share of the reduction in emissions is attained abroad. In other words, with linkages some of the benefits of environmental policy are exported as well. Yet, when the scope of pollutants is global, regulators only care about total global emissions. In that specific but important case, our negative leakage result becomes inconsequential as it is precisely offset by a smaller cutback in emissions at home[8]. Thus, whereas linkages magnify the ToT motive, they leave the degree of free-riding, as measured by the

[7] Markusen (2013) examines a special case of a two country model in which countries export 50% of the global abatement costs, but internalize only 50% of the global benefits, such that the cooperative and non-cooperative equilibrium exactly coincide. As example 4 shows, we can replicate this finding by setting $\varepsilon = 1$ and $N = 2$. Note that in general we restrict ourselves to the more realistic case of $\varepsilon > 1$.

[8] This zero-sum outcome is a direct consequence of the fact that the ToT effects wash out across countries.

marginal benefit ratio, unaffected, that is, when $\xi = 1$ we obtain $\frac{\Omega^B + (N-1)\Omega^B_f}{\Omega^B} = N$.

For local pollutants the story is more complicated. In that case, linkages tend to increase free-riding as regulators ignore the reduction in pollution damages abroad. Thus, when pollution is local linkages magnify both the ToT and free-riding motive and the overall impact of vertical linkages on the relative standard becomes ambiguous.

4.3 Vertical Linkages and Global Pollution in Equilibrium

Armed with a thorough understanding of how vertical linkages affect environmental policy, we are now ready to analyze the relationship between vertical linkages and equilibrium pollution. Here we focus on the important case of greenhouse gas emissions ($\zeta = 1$). Again, countries are assumed to be symmetric. Furthermore, let us formally define the degree of vertical specialization, inspired by Hummels et al. (2001) and Yi (2003), as the expenditure share on imports in the production of exports. To this end, we define a country's exports and imports of intermediates by $EX_j \equiv n_j p_j y_j - n_j p_j y_{jj}$ and $IM_j \equiv \sum_i n_i p_i y_{ij} - n_j p_j y_{jj}$ respectively.

Definition 1. *The degree of vertical specialization is denoted by* $\delta_j \equiv (1-\beta)\left(\frac{IM_j}{IM_j + n_j p_j y_{jj}}\right) = (1-\beta)\left(1 - \frac{\lambda_j}{\Gamma_j} P_j^{\varepsilon-1}\right)$.

While input-output linkages directly raise the upperbound on vertical specialization (extensive margin effect), lower trade costs essentially deepen the degree of vertical specialization for a given upperbound (intensive margin effect). Hence, since stronger vertical linkages and trade liberalization ($d\phi > 0$) both tend to increase the degree of vertical specialization, it will be interesting to find out how they relate exactly to global pollution. The equilibrium solutions to the latter can be obtained by substituting for (24) into (23),

$$Nnz^*_C = \frac{\tau}{\eta} \frac{b}{\frac{1}{\alpha} + (1-\beta)\, b} \quad , \quad Nnz^*_{NC} = N \frac{\tau}{\eta} \frac{b-a}{\frac{1}{\alpha} + (1-\beta)\, b} \tag{25}$$

which can then be used to characterize the net impact of stronger linkages and trade liberalization on global pollution.

Proposition 3. Vertical Linkages, Trade Liberalization and Transboundary Pollution ($\zeta = 1$).
(i) *Stronger vertical linkages strictly increase the cooperative level of pollution, but their impact on non-cooperative pollution is ambiguous,* $\frac{dz^*_C}{d(1-\beta)} > 0$ *and* $\frac{dz^*_{NC}}{d(1-\beta)} \gtreqless 0$. *Non-cooperative pollution falls relative to cooperative pollution, that is,* $\frac{d}{d(1-\beta)}\left(\frac{z^*_{NC}}{z^*_C}\right) < 0$. (ii) *Trade liberalization does not affect cooperative pollution and its impact on pollution under non-cooperation is ambiguous,* $\frac{dz^*_C}{d\phi} = 0$ *and* $\frac{dz^*_{NC}}{d\phi} \gtreqless 0$.

Regarding the impact of vertical linkages, it turns out that the scale effect and pollution elasticity effect vanish from the equilibrium solution for pollution[9]. In equilibrium, what remains is that input-output linkages raise the opportunity costs of environmental policy ($b \uparrow$), such that it becomes optimal to increase global pollution, even though linkages, by enabling the spillback channel, also make global pollution more responsive and environmental policy more effective ($(1-\beta)\, b \uparrow$)[10]. Without cooper-

[9]This property of the equilibrium sollution follows directly from our welfare specification. With log utility both the marginal benefits and the marginal damages *of pollution* are linearly increasing in real income, leaving equilibrium pollution unaffected by real income. The welfare specification at hand thus enables us to take a "neutral stance" regarding any income effects induced by vertical linkages that drive the stringency of environmental policy. Having said that, our set-up also allows for analytical solutions under iso-elasticity utility and strictly convex damage functions.

[10]Market structure may thus increase 'international interdependence' and thereby influence the extent to which countries can effectively exercise control over local and global environmental quality. See Bagwell and Staiger (2004) for a more general and formal analysis of international interdependence and national sovereignty.

ation the overall impact of vertical linkages is not as clear cut. This happens because linkages also strengthen the ToT effect ($a \uparrow$), which tends to increase the non-cooperative standard.

In general, it turns out to be difficult to characterize analytically the influence of trade liberalization and stronger vertical linkages on global pollution under non-cooperation. Therefore we resort to numerical analysis to supplement the analytical results of Proposition 3.

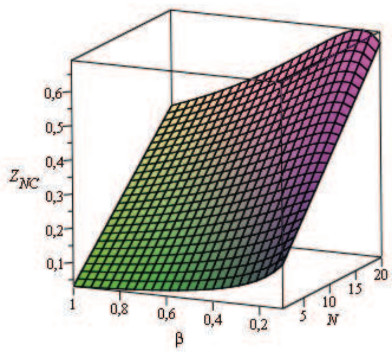

Figure 2. The non-cooperative level of pollution - the impact of β and N under free trade.

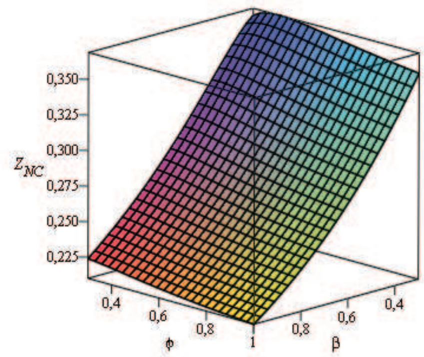

Figure 3. The non-cooperative level of pollution - the impact of β and trade costs ($N = 10$).

Numerical Example 2. Our baseline parameter values are: $m = 10$, $g = 5$, $\tau = 0.6$, $\varepsilon = 3$, $\alpha = 0.1$, $L^w = 10$ and $\eta = 2$. In figure 2 we display the non-cooperative level of pollution under free trade for different values of N and β. The results here are rather clear. First, due to free-riding pollution is strictly increasing in N. Second, vertical linkages raise global pollution, which indicates that the opportunity cost effect overwhelms the spillback channel effect and ToT effect[11]. An interesting observation from figure 3, however, is that trade liberalization lowers global pollution. This effect can be rationalized by pointing out that trade liberalization increases export intensity, enabling a higher environmental standard.

Figures 2 and 3 allow us to draw an important conclusion: stronger linkages and trade liberalization, two crucial drivers of vertical specialization, have opposite effects on global pollution. Whereas trade liberalization tends to decrease pollution, stronger linkages actually tend to increase global pollution. The reason for this intricate, yet straightforward relationship lies in the fact that even though trade liberalization and stronger linkages both magnify the ToT effect, the latter 'unfortunately' also raises the

[11] Numerical analysis reveals that linkages can also achieve the opposite and actually lower non-cooperative pollution, but only if one is willing to assume really strong linkages, a small elasticity of substitution and/or a small policy elasticity for the emission intensity of production ($\frac{1-\alpha}{\alpha}$).

opportunity cost of environmental policy, so that only trade liberalization tends to lower pollution.

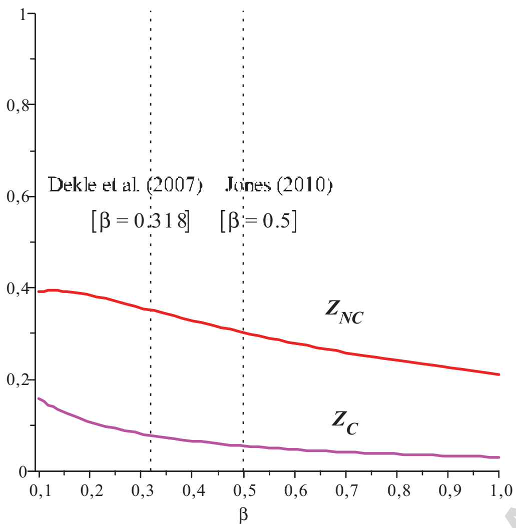

Figure 4. The cooperative and non-cooperative level of pollution - the impact of vertical linkages.

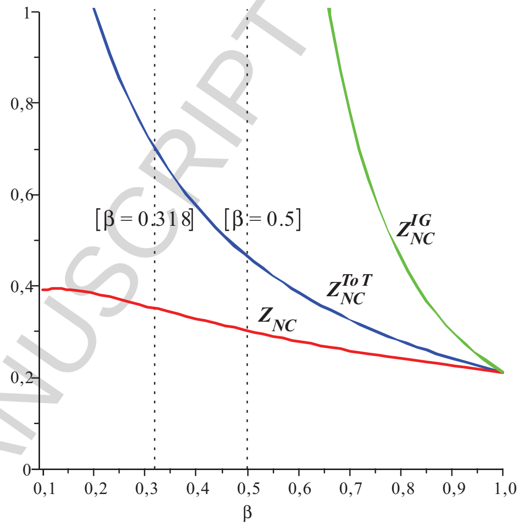

Figure 5. Ignoring vertical linkages.

Proposition 2 and 3 and the numerical results that followed thus present us with a somewhat unsettling conclusion. Despite the fact that environmental policy is strengthened when countries become increasingly interconnected, pollution tends to increase nonetheless. How can we explain this seemingly paradoxical phenomenon? At the core of this result lies again the beforementioned opportunity cost effect. In a world where countries are increasingly interconnected, domestic labor becomes increasingly productive as countries can rely on (imported) produced inputs to produce exports (see eq. (22)). This effect makes it more costly to divert resources away from production towards abatement of pollution. Because of the opportunity cost effect, the increase in the environmental standard is insufficient to match the increase in gross pollution $\bar{z}$, and net pollution increases.

Setting $N = 10$ and $\phi = 0.9$ and assuming otherwise the same parameter values as in the previous example, figure 4 depicts the relationship between vertical linkages and global pollution. Although the net effect of vertical linkages on pollution may be positive, that does not mean, however, that the ToT induced impact of vertical linkages on global pollution is quantitatively unimportant. Suppose countries set environmental policies non-cooperatively, while they ignore the fact that linkages increase the ability to export the costs of environmental policy, and let us denote the resulting level of pollution by Z_{NC}^{ToT}. Figure 5 shows that over a range of empirically reasonable values for β, adopted from Jones (2010) and Dekle et al. (2007), this level of pollution can easily be one-and-a-half times as large as in the fully informed non-cooperative outcome.

To further inspect the quantitative importance of vertical linkages, consider a policy arrangement in which national regulators fully ignore the fact that the second unbundling has arrived and continue to believe that world trade revolves around final consumer goods only. To do so, we evaluate θ_{NC}^* at $\beta = 1$, substitute it into (23) and then refer to the resulting equilibrium level of pollution as Z_{NC}^{IG}, where "IG" is a mnemonic for ignorant. As is clearly shown in figure 5, when policymakers operate under this old paradigm of "wine for cloth" (see Grossman and Rossi-Hansberg (2008)) and thus ignore the various channels through which linkages affect global pollution, the resulting standard is too weak and the gap between the optimal solution and the ignorant solution grows increasingly large when linkages become stronger.

Figure 5 makes clear that policymakers cannot ignore vertical linkages. Of course, in more realistic models the strong quantitative impact shown in figures 4 and 5 is possibly diluted. For example, in a setting with multiple sectors of production, each of them varying in the degree to which they require produced inputs, the appropriate environmental policy is likely to be an industry share weighted average of the sector-specific optimal policies. This policy could potentially differ substantially from the one examined in this paper, which is essentially shaped by the interconnectedness of the average sector.

5 Extension: Comparative Advantage and Labor Mobility

Our Armington framework served as a convenient vehicle to study the role of vertical linkages, because the strong degree of technological heterogeneity allowed us to abstract from any effects induced by domestic labor mobility. Therefore we could focus exclusively on the role of vertical linkages in inducing negative leakage. In this section we consider the robustness of our negative leakage result. To this end, we analyze a two-sector model characterized by arbitrary degrees of technological heterogeneity, thereby enabling domestic labor mobility within and between industries.

5.1 A Two-Sector Eaton-Kortum Model with Vertical Linkages

We analyze the effects of unilateral environmental policy in a Ricardian economy with one factor of production, labour, and two sectors of production, indexed by $k = 1, 2$. In each industry k there is an infinite number of varieties indexed by $v_k \in [0, 1]$. Labor is assumed to be mobile between sectors, but not across countries. Following Costinot et al. (2012), technology is assumed to be heterogenous across varieties, sectors and countries. We further extend this set-up by implementing vertical linkages, comparable to our Armington model. Here we abstract from trade costs. As before, the world consists of two (groups of) countries, country A and group B.

With two distinct sectors, let P_k be the CES price index of the composite intermediate good associated with sector k. The unit cost of variety v_k produced in country j equals:

$$p_{k,j}(v_k) = \frac{1}{g_{k,j}(v_k)} \frac{1}{1-\theta_j} w_j^{\beta} P^{1-\beta} \quad , \quad j = A, B \tag{26}$$

where $P \equiv P_1^{\gamma} P_2^{1-\gamma}$ is now a Cobb-Douglas price index of the (composite) intermediate goods from sector 1 and 2 with expenditure shares γ and $1-\gamma$ respectively. In each industry total factor productivity $g_{k,j}(v_k)$ is assumed to differ across both countries and varieties. To abstract from "factor intensity" considerations we have assumed equal input expenditure shares across industries. Environmental standards and emission intensities are assumed to be uniform across sectors. We follow Eaton and Kortum (2002) by assuming that $g_{k,j}(v_k)$ is a random variable drawn independently for each j and v_k from a Frechet distribution $F_{k,j}$ such that

$$F_{k,j}(g) = \exp\left[-\left(g/g_{k,j}\right)^{-\frac{1}{\vartheta_k}}\right]$$

where $g_{k,j} > 0$ indicates the fundamental productivity of country j in industry k and $\vartheta_k \geq 0$ is a parameter that indicates the degree of productivity dispersion across varieties in sector k. We let P serve as the numeraire. In the appendix we show how to derive the balanced trade condition, which implicitly solves for the relative wage rate $\frac{w_A}{w_B}$. Wages and prices then follow immediately.

5.2 The Effects of Unilateral Environmental Policy

To guide the comparative statics to come, let us define $h \equiv \frac{g_{1,A}}{g_{1,B}} / \frac{g_{2,A}}{g_{2,B}}$; country A holds a comparative advantage in industry 1 if $h > 1$ and a comparative advantage in industry 2 otherwise. In this two-sector setting country A's environmental policy now also influences group B's pollution levels via domestic inter-industry reallocation of labor in group B countries. Within parentheses we indicate whether leakage is determined by this labor mobility effect (m), the linkages induced spillback effect (s), both (m, s) or none ($-$). Within square brackets $[\cdot]$ we describe the set of necessary and sufficient conditions for each special case of the general model. As before, we analyze the impact of a marginal change in country A's environmental standard on leakage, i.e., the change in pollution in group B:

Proposition 4. Unilateral Environmental Policy in a Two-Sector E-K Model [$\vartheta_1 > 0$, $\vartheta_2 > 0$]. *Pollution in group B is affected by a labor mobility effect and a spillback effect (m, s). The labor mobility effect increases pollution in one industry and decreases pollution in the other industry, with the overall effect being ambiguous. The spillback effect reduces pollution in both sectors and hence always promotes negative leakage.*

Since the degree of technological heterogeneity in our model is less extreme than in the Armington setting, unilateral policies now also induce a reallocation of labor across industries. Leakage thus results from both the spillback effect and the labor mobility effect. In general, we can't proof whether comparative advantage dampens or exacerbates the spillback effect. To shed more light on (i) the conditions under which the labor mobility and spillback effects occur and (ii) the overall sign of leakage, let us consider some special cases:

Example 3. *Intra-industry trade only*; (i) *Two-sectors* [$h = 1$, $\vartheta_1 = \vartheta_2 > 0$], (ii) *One-sector* [$\gamma = 1$, $\vartheta_1 > 0$]. *For both (i) and (ii), leakage is strictly negative with linkages, but zero without linkages (s).*

Example 4. *Conditional factor price equalization (FPE)* [$\vartheta_1 > 0$, $\vartheta_2 = 0$]. *In country B some labor moves out of the differentiated goods sector and into the homogenous goods sector, and vice versa for country A. Leakage can be positive or negative* (m).

As it turns out, once the only motive to trade stems from product differentiation and the fact that technology is heterogeneous across countries but not across industries, which holds by definition in the one-sector E-K model, the comparative statics results of the E-K model are isomorphic to the one-sector Armington model. First of all, without comparative advantage unilateral environmental policy by country A does not induce any reallocation of labor *across* industries anywhere in the world.

Second, although in each industry the number of varieties produced in country B increases in response to stricter environmental policy in country A, it is also true that average production per variety goes down in each industry, leaving total production in country B unaffected. This result hinges on an important feature of the E-K model, stating that all variation across countries comes along the extensive margin, not the intensive margin, and more productive countries simply produce more varieties (see Eaton and Kortum (2002))[12]. Therefore the reallocation of labor *within* industries that takes place in all group B countries has no net effect on pollution either. If there is only intra-industry trade, the vertical linkages induced spillback effect is thus the only mechanism by which pollution abroad is affected.

Likewise, example 4 reveals that one can isolate the labor mobility effect by introducing a homoge-

[12] This does not mean that technological heterogeneity has no role to play. In the E-K model, the inverse of the technology dispersion parameter, $\frac{1}{\vartheta_1}$, replaces the preference parameter $\varepsilon_1 - 1$. If technology dispersion weakens, it becomes harder to export the costs of environmental policy and the magnitude of negative leakage diminishes. In the extreme case where technology dispersion is completely absent, the spillback channel is mute and leakage is zero.

nous outside sector. As in the full-fledged two-sector model, the general equilibrium always displays imperfect specialization by both countries. With industry 2 now being homogeneous, however, conditional FPE results. Using the terminology introduced in section 3, this implies that the positive allocation effect, which explains that the policy shock induces country B to consume relatively more intermediate inputs, exactly offsets the negative supply effect, so that the spillback effect becomes mute.

Going one step further, once both industries are assumed to produce homogenous goods, we obtain the classic two-sector Ricardian model. Various regimes of specialization are feasible: (i) imperfect specialization by A while B only produces commodity 2 (A), (ii) imperfect specialization by B while A only produces commodity 1 (B) and (iii) perfect specialization by both countries where commodity 1 and 2 are produced only in country A and B respectively (0). Let us define $r_1 \equiv \frac{1}{N-1}\frac{1-\gamma}{\gamma}\left(\frac{g_{1,A}}{g_{1,B}}\frac{1-\theta_A}{1-\theta_B}\right)^{\frac{1}{\beta}}$ and $r_2 \equiv \frac{1}{N-1}\frac{1-\gamma}{\gamma}\left(\frac{g_{2,A}}{g_{2,B}}\frac{1-\theta_A}{1-\theta_B}\right)^{\frac{1}{\beta}}$.

Example 5. *Inter-industry trade only* [$\vartheta_1 = \vartheta_2 = 0$].
(i) *Conditional FPE; zero leakage* ($-$) *in regime A* [$h > 1$, $\frac{L_B}{L_A} < r_2$], *although leakage may be positive or negative* (m) *in regime B* [$h > 1$, $\frac{L_B}{L_A} > r_1$].
(ii) *No FPE; regime* 0 [$h > 1$, $r_2 \leq \frac{L_B}{L_A} \leq r_1$]. *With linkages, leakage is strictly negative and zero otherwise* (s).

The take-home message here is *not* that the spillback effect requires extreme patterns of specialization. Instead, factor prices need to be determined through the balanced trade condition. This ensures that some of the costs of environmental policy are exported to trade partners via the ToT. When industries are homogenous, however, there is only inter-industry trade and conditional FPE emerges under fairly general conditions. As a result the spillback effect disappears. It is only when perfect specialization prevails that relative demand for imports and exports once again determines factor prices such that the spillback effect resurfaces.

By and large, the results from the Armington model with vertical linkages are thus robust to the inclusion of multiple industries and comparative advantage. Comparative advantage may imply that total leakage is positive due to labor mobility effects, but the spillback effect remains intact as long as environmental policy alters the ToT.

6 Conclusion

In this paper we have explored the role of vertical linkages on the international effects of environmental policy. When countries are mutually dependent on imports to produce exports, domestic environmental policy indirectly lowers pollution externalities in the rest of the world. This mechanism for negative leakage is robust to the inclusion of trade costs, country asymmetries and industry relocation effects.

Whether strategic interaction between national policymakers leads to levels of pollution that are inefficiently high, depends on the geographic scope of the relevant pollutant and hence on the relative strength of the terms of trade motive and the free riding motive. Although vertical linkages reinforce the ToT motive, this is never sufficient to outweigh free-riding when pollution is transboundary. Still, by strengthening the ToT externality, vertical linkages bring the non-cooperative standard relatively closer to the cooperative standard. As a direct result the non-cooperative level of pollution falls relative to the level of pollution that emerges under cooperation. In that sense, vertical linkages are good for the environment. Nevertheless, whether countries cooperate or not, when countries become increasingly interdependent via vertical linkages, the net marginal benefits of pollution grow larger and global pollution tends to increase in absolute terms.

Future work might focus on endogenizing stronger vertical linkages. No doubt, such an analysis would emphasize the role of communication technology, as lower costs of communication can enable production fragmentation (see Grossman and Rossi-Hansberg (2008)), and factor-augmenting technical change (see Karabarbounis and Neiman (2014)). Multinational corporations could be important here as well, as these firms are known to play an active role in 'establishing vertical linkages' between producers in different countries (see Ramondo and Rodriguez-Clare (2013)). For various reasons, studying optimal environmental policies with asymmetric countries and asymmetric linkages also constitutes an interesting avenue for future research. It seems likely, for example, that any agreement on burden sharing in the context of climate policies will depend strongly on cross-country heterogeneity in technology and endowments.

At the industry level, more detailed analysis of pollution intensive sectors might be a fruitful research topic too[13]. This seems especially interesting in the context of the energy and transportation sectors. These sectors are of vital importance not only to the world economy, as measured by their degree to which they are (inter)nationally linked to other sectors, but, since they are carbon intensive, also appear to be crucial to any serious plan that aims to mitigate global carbon emissions.

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Highlights

-We analyze the role of vertical linkages on the international effects of environmental policy.

-With vertical linkages, domestic environmental policy indirectly reduces pollution in the rest of the world.

-Vertical linkages influence the tension between the free-riding incentive and the terms of trade motive.

-Whether countries cooperate or not, vertical linkages tend to increase global pollution.