Can Globalization Outweigh Free-Riding?*

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Abstract

We analyze the role of input-output linkages on the effects of environmental policy in a vertically integrated world economy, an international market structure that deserves further scrutiny given its empirical relevance. We find that with vertical linkages unilateral environmental policy results in negative carbon leakage. This effect occurs because globalization, here defined as the degree of vertical integration, implies that 'total factor productivity' in the intermediate goods sector is to an increasing extent negatively affected by environmental policy abroad. In terms of its overall impact on the interplay between environmental policy and trade, however, vertical integration works somewhat like a boomerang; although negative leakage implies that the marginal benefits of environmental policy are higher under vertical integration, we show that the marginal costs are higher as well due to productivity feedback effects. We then study a non-cooperative game between governments setting environmental standards and find that at best globalization lowers the 'distance' between the social optimum and the non-cooperative equilibrium.

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

JEL classification: F18, Q56, Q58.

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1 Introduction

The nature of international trade is changing. Since the middle of the 1980s trade in intermediate goods has become one of the major features of the world economy. In addition to this trend most countries have experienced an increase in the degree to which their exports are produced with imported inputs[1]. Together, these two elements play a central role in the emergence of a global economy that, to an increasing extent, is characterized by vertical integration. The objective of this paper is to determine whether these relatively recent developments in the ongoing process of globalization shed new light on the relationship between international trade and the environment. To this end, we set up a simple multi-country general equilibrium model that captures the key elements of cross-country vertical integration. In this setting several interesting results are obtained. For example, contrary to conventional wisdom we find that unilateral climate change policy results in negative carbon leakage. Thus, accounting for vertical integration seems relevant.

Recent research in the trade literature suggests that the process of globalization has occurred in two consecutive waves. According to Baldwin (2006), *'the first unbundling allowed the spatial separation of factories and consumers. The second unbundling spatially unpacked the factories and offices themselves'*. Figure 1 shows the empirical relevance of his statements: since the end of the 1980s trade in intermediate goods and business services have increased to a far greater extent than total trade (WTO, 2008). According to Yeats (2001) intermediate input trade, or 'global production sharing', already accounted for roughly thirty percent of world trade in manufacturing goods in 1995[2].

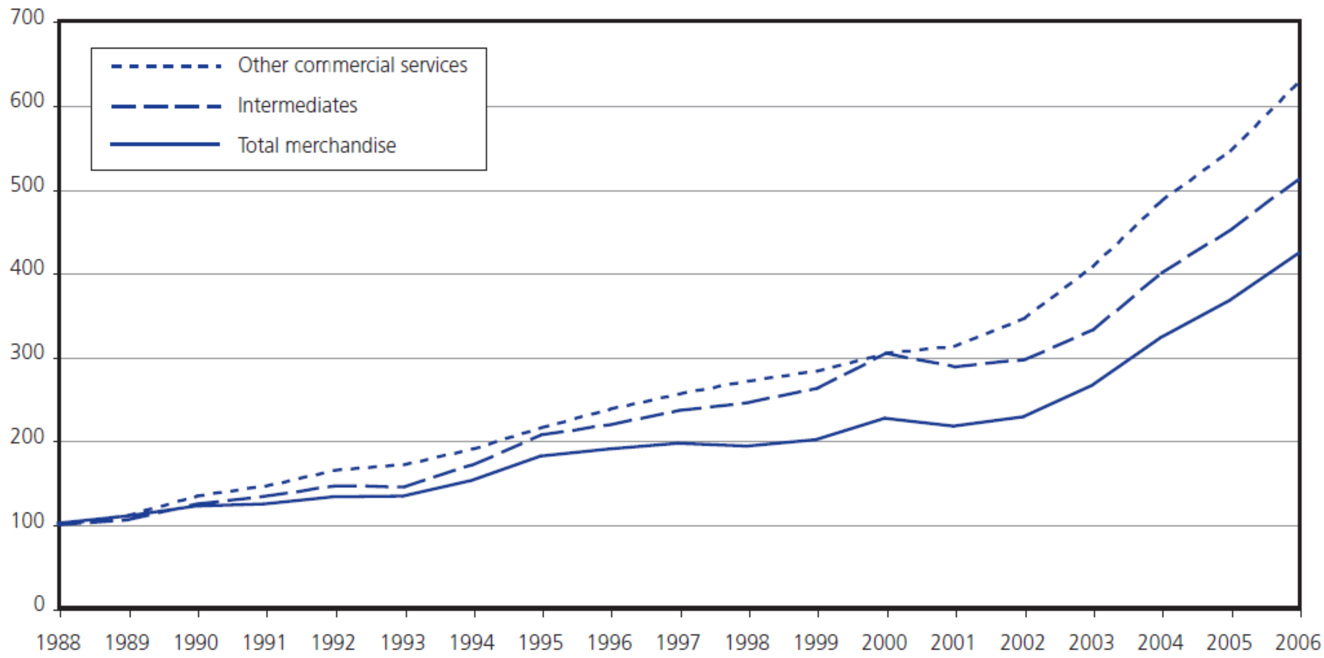

Figure 1. Trends in world trade of total merchandise, intermediate goods and commercial services. Source : WTO (2008). Note: Intermediates are classified as in Yeats (2001).

Amidst these structural changes there has been a growing concern that trade liberalization will intensify regulatory competition in environmental policies between countries, thereby provoking a race to the

[1]Note that trade in intermediate goods does not necessarily lead to an increase in the degree to which exports are produced with imported inputs. The reason is that in principle imported intermediate goods could be used to produce non-tradable goods only. This is the case in the models by Acemoglu & Ventura (2002) and Benarroch & Weder (2006).

[2]For a more thorough overview of empirical studies in the field see Antras & Staiger (2008).

bottom (see Ederington (2010)). In this respect, trade liberalization could have negative consequences for global environmental quality. In an institutional context where the WTO and its members have taken the lead in banning the use of most trade instruments, fear for such a race to the bottom does not seem irrational. This does not represent a necessary outcome, however, as some have argued that there might be a race to the top instead. If the elasticity of demand for domestic products on world markets is sufficiently low, a significant fraction of the costs of environmental policy can be passed through to foreigners via higher prices. This incentive is stronger the larger the portion of trade that crosses national borders. Based on this argument, McAusland and Millimet (2011) explain how international trade can thus be more beneficial for the environment than intranational trade.

Of course, there is a substantial amount of theoretical research that tries to determine whether trade, directly or indirectly, results in environmental degradation. The usual method of analysis here is to compare levels of pollution under autarky and under international trade, conditional on various forms of environmental policy. So far the literature has focused on this approach while other, equally relevant aspects of globalization have received fairly little attention or have been ignored altogether. In this paper we consider a novel aspect of globalization, that is, (i) the degree of vertical integration across countries in the context of trade in intermediate goods, which we complement with (ii) the degree of trade openness, a more familiar notion of globalization. Like trade liberalization, vertical integration represents a form of economic integration, but the latter is more relevant in the context of input markets. This brings us to the main question of our paper: *can the interdependency created by vertical integration outweigh free-riding between nation states in the case of transboundary pollution*? Regarding the positive effects of environmental policy we find that vertical integration (i) lowers the import elasticity of demand, thereby increasing the incentive to export the costs of environmental policy, and (ii) creates a dependence between total factor productivity in the intermediate goods sector and environmental policy abroad. The latter implies that unilateral environmental policy results in negative leakage. We then analyze a non-cooperative game between governments setting environmental standards and find that in case of global pollutants the equilibrium standard is set too low, because free-riding remains the dominant mechanism despite negative leakage and an increased possibility to exports the costs of environmental policy. We do find, however, that an increase in the degree of vertical integration limits the 'distance' between the non-cooperative standard and the standard in the social optimum. The implication of this last result is that the increasing interconnectedness between countries in manufacturing industries might lead to better environmental outcomes (i.e. green welfare) in a world where non-cooperative approaches to environmental policy remain important.

With respect to our model structure, there exists a substantial literature on vertical integration, intermediate goods and international trade. Yi (2003) uses a two-country dynamic Ricardian trade model to explain how trading (un)processed intermediate goods back and forth between countries can lead to magnification of the impact of tariffs on final goods prices. In our analysis two characteristics of a vertically integrated world economy, as in Yi (2003), stand out. First, vertical specialization requires countries to specialize in certain stages of the production sequence of a final good. Second, and as argued by Hummels et al. (2001), the use of imported intermediate goods to produce export goods is pivotal to vertical specialization. We refer to these features of the vertically integrated world economy respectively as (i) supply chain specialization and (ii) the import dependence of exports. Here we take a simple approach to the vertically integrated world economy. First, we assume that each country produces a unique set of tradable intermediate goods. In turn, the total set of world intermediates can be combined to form a composite intermediate good. In this way we introduce supply chain specialization. Second, we assume that tradable intermediate goods are produced with domestic labor and the composite intermediate good, thereby capturing the dependence of exports on imported inputs.

The rest of this paper is set up as follows. In the next section, we contrast our approach with the existing literature and preview some of our results. In section 3 we discuss the characteristics of our trade model. In section 4 we discuss the relationship between environmental policy, terms-of-trade effects, TFP effects and spillback effects, which forms the core of our analysis. This discussion is followed by a typology of the various determinants of global pollution in section 5. Here, we also explain how negative carbon leakage can arise in our model. Section 6 then compares the social optimum to the non-cooperative Nash equilibrium. We analyze various properties of the Nash equilibrium and carefully spell out the implications for global environmental quality. We then move on to discuss the effects of strengthening the international input-output structure and consider the effects of an increase in the number of countries on global welfare and green welfare in section 7. The last section concludes.

2 Literature Overview

The environmental consequences of trade in intermediate goods are relatively unexplored in the literature on trade and the environment. Some important exceptions are Benarroch and Weder (2006), McAusland (2004) and Hamilton and Requate (2004). Hamilton and Requate (2004) examine strategic environmental policy in a partial equilibrium model where exports are produced in a vertically related industry structure with a downstream and upstream sector. They conclude that if vertical contracts are allowed, the optimal environmental tax that should be levied on the polluting input is actually a Pigouvian tax. Our work is similar in the sense that we are interested in non-cooperative environmental policy in the presence of a vertical production structure. Unlike their paper, we consider international vertical structures instead of intranational vertical structures. Other important differences are our focus on general equilibrium and the input-output structure of production. Similar to our analysis, dirty intermediate goods are a central element of McAusland (2004), but her focus is more specific, i.e. environmental regulation as export promotion of an industry that is subject to economies of scale. Our focus is on non-cooperative policies in a vertically integrated world economy instead of unilateral policies for a small open economy. Benarroch and Weder (2006) consider a two-country model of trade in intermediate goods with monopolistic competition. They only consider pollution from final goods, abstract from optimal environmental policies and do not consider input-output linkages.

From a regulatory point of view, one can argue that international trade decouples the costs of environmental policy from the benefits of environmental policy when compared to a situation of autarky or interregional trade. This is because trade affects the costs, not the benefits, of environmental regulation if a certain fraction of domestically produced goods is exported. Two conditions are crucial for our argument. First, when determining the stringency of environmental regulation, the domestic regulator only internalizes the costs of environmental policy in as far they are borne by domestic producers and consumers. Second, export demand should be sufficiently inelastic such that the burden of environmental regulation falls on importers as well. Provided these conditions are met, the costs of environmental policy will fall with trade intensity. Therefore, stringent environmental policy will be easier for smaller than for large countries because ceteris paribus trade intensity is smaller for the latter. This beneficial aspect of policymaking in open economies is coined 'regulatory decoupling' by McAusland and Millimet (2011). Related themes are explored by Pflüger (2001), who finds that openness leads to stricter environmental regulation via consumer price spillovers in a model of monopolistic competition, and Haupt (2006), who extends this work to a setting with an endogenous number of varieties. We differentiate from the beforementioned contributions by connecting the tax-exporting motive to the degree of vertical integration and examining the consequences for (green) welfare.

3 The Model

The world economy consists of a (large) number of N countries indexed by j. There is one primary factor of production, labor L, that is supplied inelastically and immobile between countries, but perfectly mobile domestically. The size of the world population equals L^w. Initially, we will focus on the case with symmetric countries such that $\frac{L^w}{N} \equiv L$. The latter identity implies that in a situation of autarky ($N = 1$) we have $L = L^w$ whereas a world of small open economies ($N \to \infty$) corresponds to $L \to 0$. In each country there are three sectors, producing (1) tradable intermediate goods, (2) a composite intermediate good and (3) a non-tradable final consumption good. The latter commodity is produced using domestic labour and the composite intermediate good. Up to this point, the production structure is identical to Acemoglu and Ventura (2002). We extend their production structure by assuming that the composite intermediate good is also used as an input in the production of tradable intermediates (input-output). In this sense the model is similar to Rodriguez-Clare (2007) and Ramondo and Rodriguez-Clare (2010), who also assume an international input-output (I-O) structure[1]. In addition, we assume that the production process of tradable intermediates is polluting and that abatement can reduce the emission intensity of production.

Countries engage in two-way trade in intermediate products in order to produce the composite intermediate good. There exists a continuum of tradable intermediate goods with mass M. We assume that country j produces a unique subset n_j from this set of varieties with $\sum_{j=1}^{j=N} n_j = M$ and $n_j \cap n_k = \emptyset$ for $\forall j, k$ conditional on $j \neq k$. Again, we assume symmetry such that $n_j = n = \frac{M}{N}$. The assumption that each country produces a unique set of intermediates is simplifying, but captures the idea of supply chain specialization, a critical feature of the vertically integrated economy model.

3.1 Welfare and Consumption

Per capita welfare $u_j = u(c_j, Z_j)$ in country j is determined by per capita consumption $c_j \equiv C_j/L$ and (transboundary) pollution Z_j in the following manner:

$$u(c_j, Z_j) = \frac{{c_j}^{1-\sigma}}{1-\sigma} - \eta Z_j \ , \ \sigma > 0 \tag{1}$$

Let ϕ denote the homogenous cross-country pollution spillover coefficient such that pollution experienced by country j is defined as $Z_j \equiv nz_j + \sum_{i \neq j} \phi n z_i$ where nz_i is pollution generated by production of intermediate goods in country i. The special cases of $\phi = 0$ and $\phi = 1$ are used to denote respectively the degree of spillovers associated with local pollutants (sulfur) and global pollutants (carbon). The marginal damage from pollution η is assumed to be constant.

3.2 Production of Intermediate Goods

The constant returns to scale production function of a typical tradable intermediate good in country j is given by

$$y_j = (1 - \theta_j) {l_{jy}}^{\beta} {x_{jy}}^{1-\beta} \tag{2}$$

where y_j refers to net output, x_{jy} represents the input of the composite tradable intermediate good and l_{jy} is the input of labour. The production of one *net* unit of output 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.[3] Note

[1]Note that Rodriguez-Clare (2007) and Ramondo and Rodriguez-Clare (2010) do not consider optimal policies.

[3]The assumption that dirty sectors use a fraction of their own output to abate pollution is common in the literature on trade and the environment. A notable expection is Greaker & Rosenknut (2008). Greaker & Rosenknut (2008) introduce a seperate upstream pollution abatement sector in a partial equilibrium trade model.

that this implies that $(1-\theta_j)$ in (2) is the ratio of net output over gross output. Following Copeland and Taylor (2003) we assume a simple iso-elastic specification for the emission intensity, $e(\theta_j) = (1-\theta_j)^{\frac{1-\alpha}{\alpha}}$ with $0 < \alpha < 1$ which implies $e'(\theta_j) < 0$ and $e''(\theta_j) < 0$. Total emissions z_j of a typical variety then equal:

$$z_j = e(\theta_j) y_j \tag{3}$$

We assume the government is able to indirectly control the intensity of abatement θ_j by imposing an emission standard $\bar{s}_j = e(\bar{\theta}_j)$, where $\bar{\theta}_j$ is uniquely determined by $\bar{\theta}_j = e^{-1}(\bar{s}_j)$. In the remaining of this paper we will always refer to θ_j when discussing the stringency of environmental policy in country j.

Production of the composite intermediate good X_j takes place under constant returns to scale with a CES production technology using all available intermediate goods:

$$X_j = \left(\sum_{i=1}^{N} n y_{ij}^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}} \quad , \quad \varepsilon > 1 \tag{4}$$

where y_{ij} is the input of a typical intermediate good from country i in country j, representing an import in case $i \neq j$. The parameter ε is the elasticity of substitution between tradable intermediates. It also represents the price elasticity of foreign demand for imports and Acemoglu and Ventura (2002) interpret the inverse of this elasticity as a measure of the degree of specialization.

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

$$p_j = \frac{1}{\psi} \frac{1}{1-\theta_j} w_j{}^{\beta} P_X{}^{1-\beta} \tag{5}$$

$$P_X = \left[\sum_{i=1}^{i=N} n p_i{}^{1-\varepsilon} \right]^{\frac{1}{1-\varepsilon}} \tag{6}$$

where p_j is the intermediate goods price, P_X is the price of the composite intermediate good, w_j represents the domestic wage rate and $\psi \equiv \beta^{\beta}(1-\beta)^{1-\beta}$.

3.3 Production of the Final Good

The non-tradable consumption good C_j is produced with the input of (i) the composite intermediate good X_{jC} and (ii) labour L_{jC}:

$$C_j = \chi L_{jC}{}^{1-\tau} X_{jC}{}^{\tau} \tag{7}$$

where $\chi \equiv \tau^{\tau}(1-\tau)^{1-\tau}$ represents a parameter used for normalization. With perfectly competitive markets the price dual to (7) reads:

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

Market clearing for the composite intermediate good in each country requires $X_j = X_{jC} + X_{jy}$, where $X_{jy} \equiv n x_{jy}$ represents total input of the composite intermediate good in the intermediate goods sector.

3.4 Global Environmental Quality

To derive an expression for total pollution Z_j, we use the definition of pollution $Z_j \equiv nz_j + \sum_{i \neq j} \phi n z_i$, and substitute for total pollution per variety z_j from (3):

$$Z_j = n \left[e(\theta_j)(1-\theta_j) {l_{jy}}^{\beta} {x_{jy}}^{1-\beta} + \phi \sum_{i \neq j} e(\theta_i)(1-\theta_i) {l_{iy}}^{\beta} {x_{iy}}^{1-\beta} \right] \tag{9}$$

Total pollution depends on environmental policy at home and abroad and the input of labor and the composite intermediate good for the production of intermediate goods. Once we have solved for the market equilibrium of the model, we will return to an in-depth analysis of (9), where we will take into account the endogeneity of the various inputs.

3.5 Market Equilibrium and Trade Balance

In equilibrium the sum of labour employed in the production of tradable intermediates $L_{jy} \equiv nl_{jy}$ and the non-tradable consumption good L_{jC} should equate the supply of labour, $L = L_{jy} + L_{jC}$. Define E as world expenditures on intermediates. Demand for each tradable intermediate q_j is of the constant elasticity form,

$$q_j = {p_j}^{-\varepsilon} P_X^{\varepsilon-1} E = {p_j}^{-\varepsilon} E \tag{10}$$

where the second equality in (10) follows after taking P_X as the numeraire. Next, we examine in more detail world expenditures on intermediates. Define nominal income in country j as $I_j = w_j L$. Since in all countries (i) final goods producers spend a fraction τ of total costs on the aggregate intermediate good and (ii) intermediate goods producers spend a fraction $1-\beta$ of total costs on the aggregate intermediate good we find $E = \tau I^w + (1-\beta)\left(\sum_{j=1}^{j=N} np_j q_j\right)$, where $I^w \equiv \sum_{j=1}^{j=N} I_j$ represents world income. Equilibrium in the final goods market requires that consumption expenditures equal nominal income, that is, $p_{jC} C_j = I_j$.

Next, let us use the abbreviations IM_j and EX_j to refer to imports and exports of intermediate goods by country j. One can show that $IM_j = \frac{\tau}{\beta} I_j \left(1 - \frac{I_j}{I^w}\right)$and $EX_j = np_j^{1-\varepsilon} \frac{\tau}{\beta}\left(1 - \frac{I_j}{I^w}\right) I^w$. Equating imports and exports then leads to the balanced trade condition (see the appendix for two possible derivations):

$$I_j = n{p_j}^{1-\varepsilon} I^w \tag{11}$$

where we divided both sides of the equation by the import ratio $\frac{IM_j}{I_j}$[4]. Dividing the balanced trade condition of country j by the balanced trade condition for country i, and substituting for p_j from (5), then provides us with an expression for relative income, $\omega_{ji} \equiv \frac{w_j}{wi}$:

$$\underbrace{\omega_{ji}}_{=RD} = \underbrace{(\omega_{ji})^{\beta(1-\varepsilon)} \left(\frac{1-\theta_j}{1-\theta_i}\right)^{\varepsilon-1}}_{=RS} \Leftrightarrow \omega_{ji} = \left(\frac{1-\theta_j}{1-\theta_i}\right)^{\frac{\varepsilon-1}{1+\beta(\varepsilon-1)}} \tag{12}$$

In equilibrium, relative demand (RD) must equal relative supply of exports (RS). Whereas the former equals relative income ω_{ji}, the latter is determined by supply conditions including the ratio $\frac{1-\theta_j}{1-\theta_i}$. Equation (12) shows that the relative wage ω_{ji} depends negatively (positively) on the stringency of environmental policy at home (abroad) provided $\varepsilon > 1$. Next, by substituting for (5) into the price index

[4] One can now also show that $1-\beta$ is a measure of vertical specialization, e.g. the degree to which exports are produced with imports. To see why, note that in the appendix we show that the (aggregate) expenditure share on imported inputs in the production of exports reduces to $\frac{\left(\frac{X_{jy}}{X_j}\right) IM_j}{EX_j} = 1-\beta$.

equation (6), and rearranging, we can solve for the wage in country j as a function of technology and relative income:

$$w_j = \left[n(1-\theta_j)^{\varepsilon-1} + n \sum_{i \neq j} (1-\theta_i)^{\varepsilon-1} \omega_{ji}^{\beta(\varepsilon-1)} \right]^{\frac{1}{\beta(\varepsilon-1)}} \tag{13}$$

With the ω_{ij}'s being a function of the ratio $\frac{1-\theta_i}{1-\theta_j}$, we have now solved explicitly for w_j in (13) as a CES weighted average of TFP in the intermediate goods sector, where the weights equal the relative income term $\omega_{ji}^{\beta(\varepsilon-1)}$.

4 Environmental Policy, Terms-of-Trade and I-O linkages

Next, we analyze the effects of a unilateral marginal change in domestic environmental policy on wages and prices. We use subscript A to denote variables of the country that unilaterally changes its environmental policy and we use subscript B to refer to the other $N-1$ countries that are inactive. For country A equations (12)-(13) can then be written as:

$$w_A = \left[n(1-\theta_A)^{\varepsilon-1} + n(N-1)(1-\theta_B)^{\varepsilon-1} \omega_A^{\beta(\varepsilon-1)} \right]^{\frac{1}{\beta(\varepsilon-1)}} \tag{14}$$

$$\omega_A = \left(\frac{1-\theta_A}{1-\theta_B} \right)^{\frac{\varepsilon-1}{1+\beta(\varepsilon-1)}} \tag{15}$$

To determine the effect of a marginal change in the emission standard on the domestic wage, we totally differentiate (14) and (15) with respect to θ_A, the own wage rate w_A and the foreign wage rate w_B while taking θ_B as constant, and rearrange:

$$\widehat{w_A} = \underbrace{\frac{1}{\beta} \frac{1}{N} \widehat{(1-\theta_A)}}_{\text{=sectoral TFP effect}} + \underbrace{\frac{N-1}{N} \widehat{\omega_A}}_{\text{=BoT effect}} \tag{16}$$

$$\widehat{\omega_A} = \frac{\varepsilon-1}{1+\beta(\varepsilon-1)} \widehat{(1-\theta_A)} = \underbrace{\frac{1}{\beta} \widehat{(1-\theta_A)}}_{\text{=indirect TFP effect}} - \underbrace{\frac{1}{\beta} \frac{1}{1+\beta(\varepsilon-1)} \widehat{(1-\theta_A)}}_{\text{=ToT effect}} \tag{17}$$

where $\widehat{v} \equiv \frac{dv}{v}$ measures the relative change of a variable. By substituting for $\widehat{\omega_A}$ from (17) into (16) we obtain $\widehat{w_A}$ in terms of $\widehat{(1-\theta_A)}$. Note that this solution can then be used, together with the identity $\widehat{\omega_A} = \widehat{w_A} - \widehat{w_B}$ and equation (17), to derive $\widehat{w_B}$ as a function of $\widehat{(1-\theta_A)}$. Next, by defining the aggregate import demand elasticity of intermediate goods as $\varepsilon_D \equiv 1 + \beta(\varepsilon-1)$ we can then summarize our first set of results:

Result 1 *More stringent environmental policy reduces the domestic wage rate,*

$$\frac{dw_j}{d\theta_j} = \left[\underbrace{\frac{1}{\beta}\left(1-\frac{1}{N}\right)\frac{1}{\varepsilon_D}}_{ToT} - \underbrace{\frac{1}{\beta}}_{TFP} \right] \frac{w}{1-\theta} = (a-b)\frac{w}{1-\theta} < 0 \tag{18}$$

via a negative TFP effect ($-b\frac{w}{1-\theta} < 0$) and a positive terms-of-trade effect ($a\frac{w}{1-\theta} > 0$), where $a \equiv \frac{1}{\beta}\left(1-\frac{1}{N}\right)\frac{1}{\varepsilon_D} = \frac{1}{\beta}\frac{N-1}{N}\frac{1}{1+\beta(\varepsilon-1)}$ and $b \equiv \frac{1}{\beta}$ denote respectively the terms-of-trade coefficient and the TFP coefficient. Foreign *wages are affected as well via terms-of-trade spillovers,* $\frac{dw_i}{d\theta_j} = -\frac{1}{N-1} a \frac{w}{1-\theta} < 0$*. Prices of intermediate goods increase at home and decrease abroad,* $\frac{dp_j}{d\theta_j} = \beta a \frac{p}{1-\theta} > 0$ *and* $\frac{dp_i}{d\theta_j} = -\beta \frac{1}{N-1} a \frac{p}{1-\theta} < 0$.

Environmental policy affects the return to labour via two different channels. First, there is a TFP effect, derived from the fact that producers require more inputs to produce one net unit of output if the stringency of environmental policy increases. This effect tends to lower the wage rate. Second, since countries produce a unique set of varieties a part of the costs of environmental policy is exported in the form of higher prices. In other words, there are positive terms-of-trade effects. The overall impact of these two effects on the wage rate is unambiguously negative because the positive terms-of-trade (ToT) effect is always overwhelmed by the negative TFP effect, that is, $a - b < 0$ (Result 1).

In what way do I-O linkages change the costs of environmental policy in an open economy? According to Result 1 the degree of vertical integration, as measured by $1-\beta$, has a twofold effect on the return to labor. First, the introduction of I-O linkages changes the aggregate import demand elasticity of intermediate goods, $\varepsilon_D = \varepsilon - (1-\beta)(\varepsilon - 1) = 1 + \beta(\varepsilon - 1)$. This elasticity is the sum of a conventional sectoral *substitution effect* (ε), which indicates that producers in the composite intermediate goods sector will substitute toward other intermediate goods in response to a price increase, and a novel *expenditure effect* ($-(1-\beta)(\varepsilon-1)$). The expenditure effect explains to what extent producers of intermediate goods change their total expenditures on the composite intermediate good in response to a change in import prices, which depends on the expenditure share $1-\beta$ of the aggregate intermediate good and the elasticity of import expenditures with respect to price, $-\frac{d(p_i y_{ij})/p_i y_{ij}}{dp_i/p_i} = -(\varepsilon - 1)$. Therefore, in a world with vertical integration the aggregate import demand elasticity ε_D tends to be smaller than the sectoral import demand elasticity ε, the degree of specialization increases from $\frac{1}{\varepsilon}$ to $\frac{1}{\varepsilon-(1-\beta)(\varepsilon-1)}$, and it becomes more difficult to substitute away towards other (local) inputs. Second, the introduction of I-O linkages gives rise to an intermediate goods multiplier that increases the magnitude of both the TFP effect as well as the ToT effect:

Result 2 *Boomerang mechanism of environmental policy.*
The terms-of-trade effect and the TFP effect are monotonically increasing in the so-called 'intermediate goods multiplier' $\frac{1}{\beta} \in [1, \infty)$.

A useful interpretation of β can be given by noting that $1/\beta$ represents the intermediate goods multiplier of environmental policy[5]. Intuitively, a higher standard in country A diminishes production of intermediate goods in that country. Ceteris paribus, a lower supply of intermediate goods from A will also lower total production of the composite intermediate good around the world. A decrease in the supply of the composite intermediate good then feeds back into the intermediate goods sector and lowers output in this sector. Diminished output of intermediate goods sets in motion a new round with reduced outputs in all sectors. This cycle will repeat itself again and again. The culmination of this cycle is the geometric sequence $1 + (1-\beta) + (1-\beta)^2 + .. = \frac{1}{1-(1-\beta)} = \frac{1}{\beta} \geq 1$ which holds for any $\beta \in (0, 1]$. Interestingly, the presence of international trade does not diminish the I-O multiplier, at least not in the current setting without trade costs. Equations (16)-(17) reveal that the total TFP coefficient b is the sum of a direct sectoral TFP effect ("partial equilibrium" effect) and an indirect TFP effect (general equilibrium effect) that is channeled through the balance of trade condition. Although the direct (indirect) effect is diminishing (increasing) with country size, the overall effect is independent of N.

[5] In an I-O model of a small open economy with multiple factors of production, Jones (2010) explains how the simple I-O multiplier is a special case of a general, more complex multiplier where industries differ in the degree to which rely on the inputs of intermediate goods. Furthermore, using the 2006 edition of the OECD I-O database he concludes that for most countries "one over one minus the intermediate goods share" represents a good approximation to the true multiplier.

Note that in equation (17) we decompose the general equilibrium effect of environmental policy in an indirect TFP effect and a terms of trade effect.

To highlight the effects of N we can rearrange (18):

$$\frac{dw_j}{d\theta_j} = \underbrace{\left(-1+\frac{1}{\varepsilon}\right)\left(1+\frac{(1-\beta)(\varepsilon-1)}{1+\beta(\varepsilon-1)}\right)\frac{w}{1-\theta}}_{\text{small open economy}} - \frac{1}{N}\frac{1}{\beta}\frac{1}{\varepsilon}\left(\frac{\varepsilon}{1+\beta(\varepsilon-1)}\right)\frac{w}{1-\theta} \tag{19}$$

where the first term on the left-hand side coincides with the effect for a small open economy ($N \to \infty$). Large countries have to take into account that they consume a non-negligible portion of domestically produced dirty intermediates, hence the second term on the right-hand side of (19). Conclusively, terms-of-trade effects (of stricter environmental policy) are smaller when country size increases, $\frac{da}{dN} > 0$, a result that is not unique to our set-up and one that would arise in other models, including the monopolistic competition model of Krugman (1980), as well. An increase in trade intensity implies that a greater portion of the costs of environmental policy will be borne by foreign consumers via higher product prices, making a stringent environmental policy more attractive to the domestic government.

5 Global Pollution and I-O linkages

5.1 Determinants of Global Pollution

To clarify the relationship between I-O linkages and global pollution, we now derive closed-form solutions to (i) the production of the composite intermediate good and (ii) pollution. Demand for intermediate i by country j follows directly from (10) and is given by $y_{ij} = p_i^{-\varepsilon} X_j = p_i^{-\varepsilon}\frac{\tau}{\beta} I_j$ (see the appendix for more details). Subsequently, world demand equals $y_i = \sum_{j=1}^{N} y_{ij} = p_i^{-\varepsilon}\frac{\tau}{\beta} I^w$. A country's consumption share (or import share) $\lambda_j \equiv \frac{y_{ij}}{y_i}$ of a typical intermediate good then reads

$$\lambda_j = \frac{I_j}{I^w} \tag{20}$$

Substituting for $y_{ij} = \lambda_j y_i$ in (4) we obtain $X_j = n x_j = \lambda_j \left(\sum_i n y_i^{\frac{\varepsilon-1}{\varepsilon}}\right)^{\frac{\varepsilon}{\varepsilon-1}}$. Then we substitute for all y_i from (2) in this result, using $x_{jy} = \frac{1-\beta}{n} X_j$ and $\frac{X_i}{X_j} = \frac{\lambda_i}{\lambda_j}$, and rearrange:

$$X_j = \frac{1}{1-\beta}\left(\frac{1-\beta}{n}\lambda_j G_j\right)^{\frac{1}{\beta}} n l_y = \lambda_j \frac{1}{1-\beta}\left(\frac{1-\beta}{n} G\right)^{\frac{1}{\beta}} \tau L \tag{21}$$

where we used $G_j \equiv \lambda_j^{\beta-1}\left(\sum_i n((1-\theta_i)(\lambda_i)^{1-\beta})^{\frac{\varepsilon-1}{\varepsilon}}\right)^{\frac{\varepsilon}{\varepsilon-1}} = \lambda_j^{\beta-1} G$ and $n l_y = \tau L$. Via the composite technology term G, which represents an income weighted average of global environmental policies, a stricter domestic pollution standard spills over to other countries.

Next, we substitute $x_{jy} = \frac{1-\beta}{n} X_j$, (21) and (2) into (3) in order to derive total pollution per variety:

$$z_j = e(\theta_j)(1-\theta_j)\left[\lambda_j\left(\frac{1-\beta}{n} G\right)^{\frac{1}{\beta}}\right]^{1-\beta} l_y \tag{22}$$

Under full symmetry (22) reduces to $z(\theta) = \bar{z}(1-\theta)^{\Phi}$, where $\bar{z} \equiv \left(\frac{1}{N}\frac{1-\beta}{n} M^{\frac{\varepsilon}{\varepsilon-1}}\right)^{\frac{1-\beta}{\beta}} l_y$ and $\Phi \equiv \frac{dz}{d(1-\theta)}\frac{1-\theta}{z} = \frac{(1-\alpha)\beta+\alpha[1-(1-\tau)(1-\sigma)]}{\alpha\beta} > 0$. From equation (22) we learn that z_j, and by definition also

Z_j, depends (indirectly) on global environmental policies and the world income distribution, that is, $z_j = z_j(\theta_1, \theta_2, .., \theta_N, \lambda_1, \lambda_2, .., \lambda_N)$. Note that I-O linkages affect the relationship between environmental policy and pollution in two ways. First, pollution in country j expands with relative income through the term $(\lambda_j)^{1-\beta}$ (a global *composition effect*). Second, pollution diminishes with the stringency of environmental policy around the globe via G (a *technique effect*).

5.2 Weak Links and Negative Carbon Leakage

We are interested in the impact of a unilateral marginal change in environmental policy on equilibrium pollution, both at home and abroad. From the perspective of the mitigating country we can write domestic pollution and foreign pollution, using (22), as:

$$\begin{aligned} z_A &= e(\theta_A)(1-\theta_A)\left[\lambda_A\left(\frac{1-\beta}{n}G\right)^{\frac{1}{\beta}}\right]^{1-\beta} l_y \\ z_B &= e(\theta_B)(1-\theta_B)\left[\lambda_B\left(\frac{1-\beta}{n}G\right)^{\frac{1}{\beta}}\right]^{1-\beta} l_y \end{aligned} \tag{23}$$

where $G = (n((1-\theta_A)(\lambda_A)^{1-\beta} + (N-1)(1-\theta_B)(\lambda_B)^{1-\beta})^{\frac{\varepsilon-1}{\varepsilon}})^{\frac{\varepsilon}{\varepsilon-1}}$, $\lambda_A = \frac{I_A}{I^w}$ and $\lambda_B = \frac{I_B}{I^w}$. Let us define carbon leakage as the increase in emissions outside the country taking actions related to mitigation and define the following elasticities, $\varepsilon_{z,\theta} \equiv -\frac{dz_j}{d\theta_j}\frac{1-\theta_j}{z_j} = \frac{1}{\alpha}(1-\alpha(1-\beta)(a-b)) > 0$ and $\varepsilon^l_{z,\theta} \equiv -\frac{dz_i}{d\theta_j}\frac{1-\theta_j}{z_i} = (1-\beta)\frac{a}{N-1} > 0$, where superscript l is a mnemonic for leakage[6]. Some interesting characteristics of these elasticities of (global) pollution are documented in the following result:

Result 3 *Desensitization of pollution with respect to local environmental policy.*
If the number of countries increases ($N \uparrow$):
(i) pollution in any given country becomes less responsive to local environmental policy ($\frac{d\varepsilon_{z,\theta}}{dN} < 0$ and $\frac{d\varepsilon^l_{z,\theta}}{dN} < 0$).
(ii) the responsiveness of global pollution is (strictly) negative ($\frac{d(\varepsilon_{z,\theta}+\phi(N-1)\varepsilon^l_{z,\theta})}{dN} = -(1-\phi)(1-\beta)\frac{da}{dN} \leq 0$).
An increase in the degree of vertical integration ($\beta \downarrow$):
(iii) increases the responsiveness of pollution in any given country to local environmental policy ($\frac{d\varepsilon_{z,\theta}}{d\beta} < 0$ and $\frac{d\varepsilon^l_{z,\theta}}{d\beta} < 0$).

In our view, result 3 describes an important and a somewhat overlooked aspect of environmental policy in open economies. The fact that local pollution become less responsive to local policies in a globalized world represents a separate pathway through which trade affects green welfare. The question whether a country can (effectively) exercise control over its domestic affairs is related to the concept of national sovereignty. Following Krasner (1999), Bagwell and Staiger (2004) use four distinct ways to define sovereignty in order to evaluate how sovereignty and international efficiency conflict in a two-country model of international interdependence (e.g. trade interactions). Especially relevant here is their definition of *interdependence sovereignty*, which 'refers to the scope of activities over which states can effectively exercise control' (Bagwell and Staiger, 2004). In our setting this relates to the question whether countries can effectively exercise control over local environmental quality. Result 3 shows us that in a globalized world countries loose control not only over domestic pollution ($\frac{d\varepsilon_{z,\theta}}{dN} < 0$), but are also faced with a decreasing impact on what happens abroad ($\frac{d\varepsilon^l_{z,\theta}}{dN} < 0$). Nevertheless, in the case

[6]Note that these elasticities are evaluated in the symmetric equilibrium.

of global warming ($\phi = 1$) a nation's control over global environmental quality is unaffected, that is, $\frac{d(\varepsilon_{z,\theta}+\phi(N-1)\varepsilon^{l}_{z,\theta})}{dN} = 0$.

Next, we totally differentiate (23), subject to the definitions of G, λ_A and λ_B, with respect to θ_A, w_A and w_B, taking θ_B as given. Even though income shares will be independent of environmental policy in equilibrium due to our symmetric set-up ($\lambda_j = \frac{1}{N}$), ex-ante countries will take into account that they can affect relative income[7]. We can then state the following proposition:

Proposition 1 *Under a unilateral marginal increase in the stringency of environmental policy:*
1) pollution is affected by (i) a weak link effect and (ii) a global technology effect. The weak link effect decreases pollution at home but increases pollution abroad. The global technology effect decreases pollution in all countries.
2) pollution is reduced at home, that is, $\frac{dz_j}{d\theta_j} = -\varepsilon_{z,\theta}\frac{z}{1-\theta} < 0$.
3) (carbon) leakage is negative, $\frac{dz_i}{d\theta_j} = -\varepsilon^{l}_{z,\theta}\frac{z}{1-\theta} < 0$ *if and only if* $\beta < 1$. *There is zero leakage* ($\frac{dz_i}{d\theta_j} = 0$) *if there is no I-O structure* ($\beta = 1$).

To understand these results, consider the following interpretation of the global technology effect. Like physical capital, intermediate goods are produced inputs. If a country reduces its supply of intermediate goods, imports of these goods by trading partners will fall. This reduction of imports represents a reduction of inputs and ceteris paribus output in the importing country must decrease. As a result, pollution in the intermediate goods sector diminishes. Since the global technology effect affects all countries alike, domestic environmental policy thus results in a positive spillback effect in the form of reduced pollution abroad.

The weak link effect on the other hand describes a substitution effect and induces more (less) pollution abroad (at home): if productivity in the intermediate goods sector in one country decreases, then it follows from (21) that the 'intake' of intermediate goods in all other countries increases since it is more efficient to 'fuel' the more productive sectors. Thus, the weak link effect tells us that a decrease in the supply of intermediate goods from one country is softened by an increase in supply abroad[8].

Taken together, pollution decreases at home since both the weak link effect and the global technology effect diminish pollution in the mitigating country. In the rest of the world the weak link effect raises pollution, but the global technology effect reduces pollution. The net effect, however, on pollution in the rest of the world is always negative.

Unilateral policy resulting in negative carbon leakage is an interesting outcome. Most studies on climate change policies in open economies find the opposite result of positive leakage. As far as we know, Fullerton et al. (2011) is the only other paper that presents a mechanism for negative leakage[9]. In their model it results from a so-called abatement resource effect; by increasing its demand for the internationally mobile clean factor of production, the regulated sector in the mitigating country crowds out production in the unregulated sector abroad. Similar to Fullerton et al. (2011) we do not claim that carbon leakage actually is negative. Our results merely illustrate that conventional models might have overlooked certain channels. Note that one could easily introduce positive carbon leakage by modifying our basic set-up. For example, one could assume pollution in other sectors or assume a more complicated production function for final goods.

[7]Only in a world with small open economies ($N \rightarrow \infty$) will policymakers ignore this effect.

[8]Jones (2011) uses the phrase 'weak link' in a closed economy I-O model to explain how complementarities in a production chain can explain income differences between countries via misallocations of production factors. The weak link effect described here is somewhat different in that (i) we focus on international I-O links and (ii) we assume that intermediates are imperfect substitutes.

[9]In contrast to our study, Fullerton et al. (2011) do not consider strategic interaction between countries nor do they derive welfare results in the context of non-cooperative policies.

6 Environmental Policy in the Global Economy

6.1 A Variety of Externalities

Before we analyze the Nash equilibrium and the social optimum in more detail, it is helpful to list the various externalities that are present in our framework:

1. *Local pollution externality.* Firms do no take into account, unless corrective policy is in place, that the production of intermediate goods pollutes the (local) environment.
2. *Transboundary pollution externality.* Firms (and governments) do not take into account that pollution spillovers from domestic production reduce welfare in other countries.
3. *Terms-of-trade externality.* Governments take into account that a higher standard raises prices of inputs for domestic producers, but ignore the fact that price increases also fall on intermediate good producers and final good producers in other countries. Thus, they ignore the negative ramifications of higher prices on welfare in other countries.
4. *Spillback externality.* A higher domestic standard affects pollution in the rest of the world through the weak link effect and the global technology effect (see proposition 1). Governments do not internalize the implications of these indirect effects for welfare in other countries.

Given these different types of externalities, how then is the non-cooperative standard distorted? First of all, the implications of (1)-(2) are obvious. In the absence of global coordination on environmental policy, (1)-(2) tends to result in too much pollution from a social planner perspective. Second, ignoring price spillovers from domestic environmental policy can actually lead to too little pollution (3). Third and finally, (4) needs some additional explanation before proceeding to the analysis of the Nash equilibrium. The impact of environmental policy on the productivity term G in the tradable goods sector can be categorized as a negative technology spillover. This negative technology spillover will ceteris paribus decrease pollution in other countries, which in turn lowers pollution spillovers to the domestic country. We refer to this additional effect as a *spillback* effect, similar to Ogawa and Wildasin (2009), and it tends to raise the optimal standard. However, since countries will only internalize this spillback effect in as much it lowers their own pollution damages there is a tendency for too much pollution[10]. For future reference, we loosely define free riding as the joint incentive underlying pollution policy as shaped by both the spillback externality and the transboundary pollution externality.

6.2 The Social Optimum

Before proceeding to the analysis of the social optimum we feel some remarks with respect to the utility function are in order. In this section and the next we focus on solutions with log-utility ($\sigma = 1$). Under different circumstances ($\sigma \neq 1$), there is a very strong tendency for the (non-cooperative) standard to increase when β decreases due to income effects[11]. Since we are not directly interested in the impact of income on the stringency of environmental regulation, we decide to adopt a log-utility function such that the marginal cost of meeting the domestic standard (MAC) will not depend on the wage rate.

[10] In this sense, the spillback externality can also be interpreted as an extension to the transboundary pollution externality.

[11] To see why, we derive an implicit equation for the wage rate as a function of domestic environmental policy and foreign wages by rewriting the balanced trade condition (11) to:

$$(w_j)^{1+\beta(\varepsilon-1)} - n(1-\theta_j)^{\varepsilon-1} w_j = n(1-\theta_j)^{\varepsilon-1} (\sum_{i \neq j} w_i) \quad (24)$$

When countries are fully symmetric wages must equalize and (24) boils down to:

$$w = [(1-\theta) M^{\frac{1}{\varepsilon-1}}]^{\frac{1}{\beta}} \quad (25)$$

Let us define global welfare by $u^w \equiv \sum_{j=1}^{N} u_j$. Then substitution of (1), $c_j = \frac{w_j}{p_{jC}} = w_j^\tau$ and (22) into u^w leads to

$$V^w = \sum_{i=1}^{N} \log w_i^\tau - \eta \sum_{i=1}^{N} Z_i(\theta_1, \theta_2, .., \theta_N, \lambda_1, \lambda_2, .., \lambda_N) \tag{26}$$

To ease comparison with the non-cooperative equilibrium, we decide to analyze the market implementation of the social optimum where each country selects a standard that equates the social marginal cost of abatement to the social marginal benefit of abatement[12]. We maximize (26) with respect to θ_j, and rearrange to obtain:

$$\underbrace{-\tau \left(\frac{1}{w_j} \frac{dw_j}{d\theta_j} + (N-1) \frac{1}{w_i} \frac{dw_i}{d\theta_j} \right)}_{\equiv MAC_j^S} + \underbrace{\eta n \left(\frac{dZ_j}{d\theta_j} + (N-1) \frac{dZ_i}{d\theta_j} \right)}_{\equiv -MB_j^S} = 0 \tag{27}$$

where $\frac{dZ_j}{d\theta_j} = \frac{dz_j}{d\theta_j} + \phi\,(N-1)\,\frac{dz_i}{d\theta_j}$ and $\frac{dZ_i}{d\theta_j} = \frac{dz_i}{d\theta_j} + \phi \frac{dz_j}{d\theta_j} + \phi\,(N-2)\,\frac{dz_i}{d\theta_j}$. The first term on the left-hand side represents the social marginal cost of meeting the standard in util terms with a minus sign in front of it, that is, $MAC_j^S = -\tau \frac{1}{w_j} \frac{dw_j}{d\theta_j}$. A higher standard reduces wages at home and abroad, thereby reducing consumption and utility in all countries. The second term represents the marginal benefit of setting a standard or the marginal reduction in pollution damages from a higher standard. The marginal benefit of setting a higher standard in country j results from less pollution damages at home, which consist of a direct effect via $\frac{dz_j}{d\theta_j}$ and a spillback effect via $\phi\,(N-1)\,\frac{dz_i}{d\theta_j}$. In addition there are benefits in all other $N-1$ countries consisting of a direct leakage effect via $\frac{dz_i}{d\theta_j}$ and indirectly due to various spillovers via $\phi \frac{dz_j}{d\theta_j} + \phi\,(N-2)\,\frac{dz_i}{d\theta_j}$. Before we present the solution to the optimal standard in the social optimum θ^S, we analyze the non-cooperative problem.

6.3 The Symmetric Nash Equilibrium

For the non-cooperative Nash equilibrium the problem of country $j = 1, .., N$ is to maximize $V_j = \log w_j^\tau - \eta Z_j(\theta_1, \theta_2, .., \theta_N, \lambda_1, \lambda_2, .., \lambda_N)$ with respect to θ_j taking the standards set by other countries as given. The solution θ_j^{NC} satisfies the following first-order condition

$$\underbrace{-\tau \frac{1}{w_j} \frac{dw_j}{d\theta_j}}_{\equiv MAC_j} + \underbrace{\eta n \frac{dZ_j}{d\theta_j}}_{\equiv -MB_j} = 0 \tag{28}$$

for all $j = 1, .., N$ with $\frac{dZ_j}{d\theta_j} = \frac{dz_j}{d\theta_j} + \phi(N-1)\frac{dz_i}{d\theta_j}$. Like the social planner, each country will set the marginal cost of meeting the domestic standard (first term) equal to the marginal benefits of meeting the domestic standard (second and third term) when determining the optimal standard. Unlike the social planner, however, individual countries do not internalize the various externalities as listed at the beginning of this section. Now let us introduce the following notation:

Definition 1. *(i) In the symmetric non-cooperative equilibrium the marginal cost of meeting the domestic stan-*

Keep in mind that w does not depend on σ. Now from (25) note first that $\lim_{\beta \to 0} w = \lim_{\beta \to 0} [(1-\theta) M^{\frac{1}{\varepsilon - 1}}]^{\frac{1}{\beta}} = +\infty$ if $(1-\theta) M^{\frac{1}{\varepsilon-1}} > 1$. Provided this is the case one also finds, using (1), that $\lim_{\beta \to 0} \frac{\partial u}{\partial c} = (w_j)^{-\sigma\tau} = 0$. In words, the marginal utility of consumption goes to zero. As we will see later on, unless we take a log-functional form for utility, the marginal cost of abatement will then go to zero as well when we strengthen the international I-O structure (lower β).

[12]Note that in the presence of international trade it is not sufficient to use private marginal cost of abatement (as it would be under autarky). Via trade a part of the costs from environmental policy automatically spill over to other countries in the form of higher prices.

dard and the marginal benefits of meeting the domestic standard in each country can be defined as functions of N, that is, $MAC(N) = \Omega^C(N)\frac{1}{1-\theta}$ *and* $MB(N) = \Omega^B(N)(1-\theta)^{\Phi-1}$*, where* $\Omega^C(N) \equiv -\tau(a-b)$ *and* $\Omega^B(N) \equiv \eta n(\varepsilon_{z,\theta} + \phi(N-1)\varepsilon^l_{z,\theta})\bar{z}$ *denote the MAC-coefficient and MB-coefficient respectively.*
(ii) *For the social optimum we define* $MAC^S(N) = \Omega^C_S(N)\frac{1}{1-\theta}$ *and* $MB^S(N) = \Omega^B_S(N)(1-\theta)^{\Phi-1}$ *with* $\Omega^C_S = \Omega^C(1) = \tau b$ *and* $\Omega^B_S(N) = \Omega^B(N) + (N-1)\Omega^B_l(N)$*, where* $\Omega^B_l(N) \equiv \eta n\left[\phi(\varepsilon_{z,\theta} + (N-2)\varepsilon^l_{z,\theta}) + \varepsilon^l_{z,\theta}\right]\bar{z}$.

From (27) and (28), while making use of definition 1, we can now obtain closed-form solutions for θ^S and θ^{NC}:

$$\theta^{NC} = 1 - \left[\frac{\Omega^C(N)}{\Omega^B(N)}\right]^{\frac{1}{\Phi}} \quad , \quad \theta^S = 1 - \left[\frac{\Omega^C(1)}{\Omega^B(N) + (N-1)\Omega^B_l(N)}\right]^{\frac{1}{\Phi}} \tag{29}$$

In turn, these solutions can be used to solve for Z^S and Z^{NC} by substituting from (29) into (**??**). The solutions under (29) satisfy the following properties[13]:

Proposition 2 *(i) Under transboundary pollution (*$\phi > 0$*) we find* $\theta^S \gtrless \theta^{NC} \Leftrightarrow (N-1)\Omega^B_l(N)\Omega^C(N) \gtrless a\tau\Omega^B(N)$.
(ii) Under purely local pollution ($\phi = 0$*) we have* $\theta^S < \theta^{NC}$.
(iii) There exists a unique $\bar{\phi} \equiv \frac{1}{N-1}\frac{a\varepsilon_{z,\theta} + (a-b)(N-1)\varepsilon^l_{z,\theta}}{(b-a)(\varepsilon_{z,\theta} + (N-2)\varepsilon^l_{z,\theta}) - a\varepsilon^l_{z,\theta}}$ *such that* $\theta^S \gtrless \theta^{NC}$ *for all* $\phi \gtrless \bar{\phi}$ provided $\bar{\phi} \in (0,1]$.

Proposition 3 *For* $\phi < (>)\bar{\phi}$ *we find that green welfare is higher (lower) in the non-cooperative equilibrium than in the social optimum.*

Both a race to the bottom type of result, which is typical for the tax competition literature, and a race to the top result, where standards are actually higher in the non-cooperative solution than in the social optimum, are feasible depending on various parameter values. A more detailed examination of the condition under (i) might prove to be insightful here. A comparison of the two solutions under (29) tells us that the marginal cost of meeting the standard are smaller under non-cooperation than in the social optimum, which is strictly due to the terms-of-trade externality. Based on this argument alone, the non-cooperative standard should be more stringent than the standard in the social optimum. On the other hand, the marginal benefits of meeting the environmental standard are larger in the social optimum, which is due to the internalization of the transboundary pollution externality and the spillback externality. These effects work through the term $(N-1)\Omega^B_l(N)$ and they tend to make the socially optimal standard higher than the non-cooperative standard. Thus, when the terms-of-trade externality overwhelms the free-riding externality we obtain a race to the top result ($\theta^S < \theta^{NC}$) otherwise we obtain a race to the bottom result ($\theta^S > \theta^{NC}$).

If pollution spillovers between countries are absent *(*$\phi = 0$*)* non-cooperation always leads to a race to the top. How can we explain this result using our list of cross-country externalities? First, note that free-riding between nation states does not play any role when pollution is purely local. Second, under non-cooperation countries do not internalize the pollution spillback effects from a stringent standard that positively affect welfare in other countries; these spillback effects are more important when I-O linkages are strong and the number of countries increases. Third, countries impose production standards to raise the terms-of-trade. It can be shown that the terms-of-trade effect always outweighs the spillback effect and a race to the top ensues.

Part (iii) of proposition 2 shows that there exists a threshold value $0 < \bar{\phi} \leq 1$ for the spillover

[13] Note that θ^S is still a function of N since the marginal benefits of abatement depend on N: we have assumed that $\phi \in [0,1]$ such that ceteris paribus a more decentralized world leads to lower damages.

coefficient such that for all $\phi < (>)\bar{\phi}$ we obtain a race to the top (race to the bottom) result. Although it is difficult to prove analytically, numerical analysis indicates that $\bar{\phi}$ is decreasing in β. In words, the strength of the I-O structure of the world economy increases the range of values of ϕ for which the non-cooperative standard leads to inefficiently high levels of environmental protection. Finally, from the definition of $\bar{\phi}$ we note that even with transboundary pollution it is possible that green welfare is highest in the non-cooperative equilibrium provided $\phi < \bar{\phi}$.

7 Global Welfare, Green Welfare and other properties of the Nash equilibrium

[WORK IN PROGRESS]

Next, let us discuss a few interesting properties of the non-cooperative standard under transboundary pollution. Our interest goes out to the impact of the number of countries (N) and the impact of I-O linkages (β). First of all, analytically we find that the non-cooperative solution is ambiguous with respect to N ($\frac{d\theta^{NC}}{dN} = -\frac{1}{\Phi}\left(\frac{\Omega^C}{\Omega^B}\right)^{\frac{1}{\Phi}}\left(\frac{d\Omega^C/dN}{\Omega^C} - \frac{d\Omega^B/dN}{\Omega^B}\right) \gtrless 0$). While a large number of countries ($N \uparrow$) increases the extent of regulatory decoupling ($\Omega^C \downarrow$) it also exacerbates the free-riding motive ($\Omega^B \downarrow$). Using (29) we also find that stronger I-O linkages potentially lead to a higher non-cooperative standard ($\frac{d\theta^{NC}}{d\beta} \gtrless 0$). How can we explain this ambiguity? We find that the effect of a marginal change in β on the marginal cost (benefit) of meeting the domestic standard is always negative (ambiguous), that is, $\frac{d\Omega^C}{d\beta} < -\frac{1}{\beta}\frac{1}{N}b < 0$ and $\frac{d\Omega^B}{d\beta} \gtrless 0$. Even more interesting, when production technology is characterized by a strong I-O structure then the strength of the free-riding effect is possibly reduced, that is, $\frac{d}{d\beta}(\frac{d\theta^{NC}}{dN}) \lesseqgtr 0$.

To explore the ambiguity of our results in more detail, we conduct some numerical experiments. Figure 1 depicts the level of the non-cooperative standard as a function of the degree of centralization (N) and the strength of the I-O linkages (β). We take the following parameters: $\alpha = 0.3$, $\tau = 0.5$, $\varepsilon = 2$, $M = 1$, $L^w = 10$ and $\eta = 10$. The following observations stand out:

- Ceteris paribus a high number of countries lowers the non-cooperative standard.
- Stronger I-O linkages reduce the non-cooperative standard.
- The negative impact of a larger number of countries on the non-cooperative standard does not seem to be affected by the strength of the I-O structure.

The first observation tells us that, even though we have not been able to derive an analytical proof, the non-cooperative standard decreases monotonically when the number of countries increases. We also find that a stronger I-O structure decreases the optimal standard. So far we have not been able to find parameter values that show otherwise. The third observation explains that even though in theory a stronger I-O structure could mitigate the negative effects of decentralization, our numerical experiments indicate that the overall effect is likely to be small ($\frac{\partial}{\partial \beta}(\frac{\partial \theta^{NC}}{\partial N}) \approx 0$).

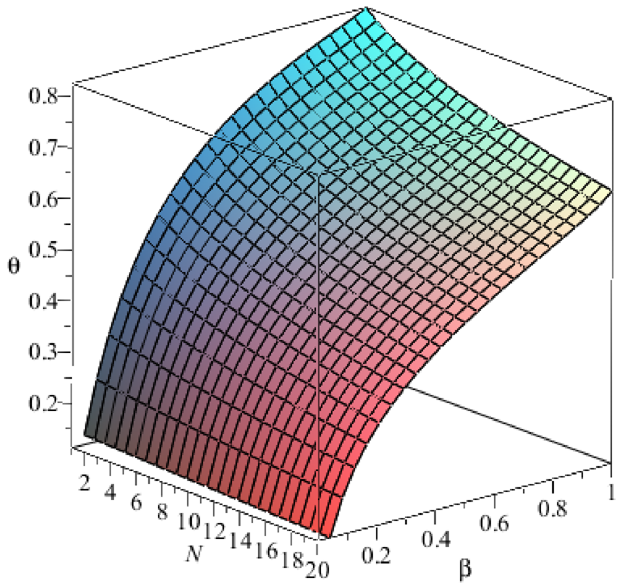

Figure 1a: The impact of the number of countries & IO-linkages on the optimal standard

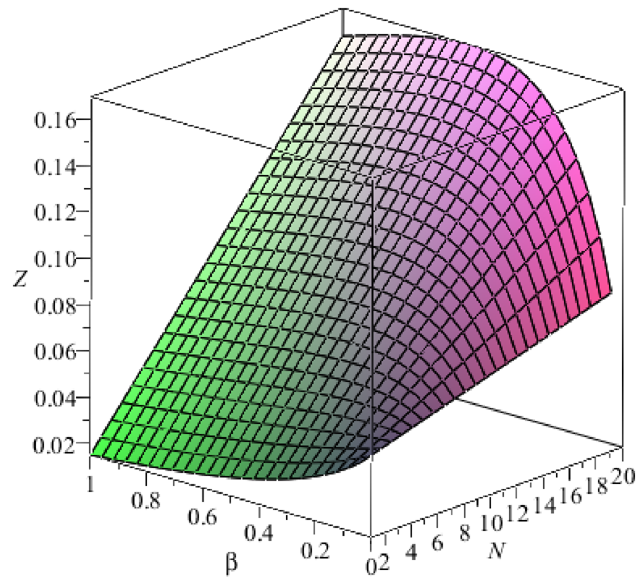

Figure 1b: Can IO-linkages reduce global pollution?

Like the equilibrium properties of the non-cooperative standard, signing the derivatives of equilibrium pollution with respect to N and β is not trivial. A change in the strength of the I-O structure of the world economy, as captured by the parameter β, affects world pollution by changing the magnitude of the various composition and technique effects that we identified; a higher β decreases emission intensity ($e(\theta) \downarrow$) and decreases the ratio of net output over gross output ($(1-\theta) \downarrow$), but has an ambiguous effect on the total input (and production) of the composite intermediate good due to a positive market share term ($\lambda^{1-\beta} \uparrow$), a positive composition effect ($(1-\beta)^{\frac{1-\beta}{\beta}} \uparrow$) and an ambiguous global technology effect ($G^{\frac{1-\beta}{\beta}} \uparrow\downarrow$). All in all, the total effect on world pollution of a change in β is ambiguous.

We depict the effects of N and the strength of I-O linkages on global pollution in figure 1b. Again, the results that follow from this numerical exercise are clear. First, the level of global pollution is increasing in the number of countries. As was evident from the explanation following proposition 2, this is caused by the overwhelming impact of free-riding on the willingness to reduce emissions. Second, and closely related to the previous observation, a larger number of countries increases global pollution, but the extent to which this happens is reduced if I-O linkages are stronger (low β). Note that for high levels of decentralization the effect of β on global pollution is u-shaped: at low levels of vertical integration a decrease in β raises pollution but once β is sufficiently small further decreases actually lower pollution. Thus, even though environmental policy is less stringent when I-O linkages are stronger (see figure 1a), numerical experiments indicate that for most parameter values the effects on global pollution are actually positive: strong linkages eventually reduce pollution, especially when decentralization is high.

8 Extensions

[WORK IN PROGRESS]

8.1 I. Trade Costs

8.2 II. Abatement as a Non-Tradable Commodity

8.3 III. Vertical Linkages and the Effects of Environmental Policy under Endogenous Pattern of Specialization

9 Conclusion

We studied the role of vertical linkages on the interplay between environmental policy and international trade, and were able to analyze the implications for global pollution and global welfare. A surprising result is that in a world with trade in intermediate goods and vertical linkages, mitigating countries do not have to worry about carbon leakage. Stringent regulation lowers the supply of intermediate goods to world markets. Since intermediate inputs, like physical capital, are produced inputs a decrease in their supply will lower pollution in the importing countries.

We also found (i) that whether global environmental quality is higher in the social optimum or the non-cooperative equilibrium depends on the degree to which pollution extends across boundaries and (ii) that I-O linkages reduce the difference between these equilibria. Nevertheless, in case of fully transboundary pollution a race to the bottom can not be prevented, even if one is willing to assume an unrealistically strong I-O structure. Thus, in the absence of global cooperation underprovision of global environmental quality remains an important issue. Using numerical analysis we then showed that, even though I-O linkages do not outweigh the impact of free-riding on the stringency of environmental policy, these linkages effectively magnify the productivity loss that is caused by global emission standards, thereby reducing global pollution. On a somewhat different note, we were able to show that local pollution becomes less responsive to local policy in a globalized world, which represents a novel pathway through which trade affects green welfare. It was then explained that vertical integration limits this process of desensitization.

The model used in this chapter was deliberately simple, thereby allowing for a range of analytically tractable results. Future work might focus on the implications of models where specialization patterns are endogenous, as well as examining the case with an endogenous number of global varieties. Another point of interest is to repeat the analysis with asymmetric countries. Probably more interesting is a more detailed assessment of climate change policies in the presence of both international (and national) I-O structures (see Leontief (1970) and Levinson (2009)). At the industry level, more detailed analysis of sectors involving trade in intermediate goods might be a worthwhile endeavor as well[14]. This seems especially interesting in the context of certain sectors, such as energy and transportation. These sectors seem of vital importance not only to the world economy, as measured by the degree to which they are linked to other sectors in the global economy, but, since they are very carbon intensive, are also crucial for mitigation of climate change.

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10 Appendix

10.1 Proofs of Results and Propositions

Result 1 *More stringent environmental policy reduces the domestic wage rate,*

$$\frac{dw_j}{d\theta_j} = \left[\underbrace{\frac{1}{\beta}\left(1-\frac{1}{N}\right)\frac{1}{\varepsilon_D}}_{ToT} - \underbrace{\frac{1}{\beta}}_{TFP}\right]\frac{w}{1-\theta} = (a-b)\frac{w}{1-\theta} < 0 \tag{30}$$

via a negative TFP effect ($-b\frac{w}{1-\theta} < 0$) *and a positive terms-of-trade effect* ($a\frac{w}{1-\theta} > 0$)*, where* $a \equiv \frac{1}{\beta}\left(1-\frac{1}{N}\right)\frac{1}{\varepsilon_D} = \frac{1}{\beta}\frac{N-1}{N}\frac{1}{1+\beta(\varepsilon-1)}$ *and* $b \equiv \frac{1}{\beta}$ *denote respectively the terms-of-trade coefficient and the TFP coefficient. Foreign wages are affected as well via terms-of-trade spillovers,* $\frac{dw_i}{d\theta_j} = -\frac{1}{N-1}a\frac{w}{1-\theta} < 0$*. Prices of intermediate goods increase at home and decrease abroad,* $\frac{dp_j}{d\theta_j} = \beta a\frac{p}{1-\theta} > 0$ *and* $\frac{dp_i}{d\theta_j} = -\beta\frac{1}{N-1}a\frac{p}{1-\theta} < 0$.

Proof By substituting for $\widehat{\omega_A}$ from (17) into (16) we obtain $\widehat{w_A} = -(a-b)\widehat{(1-\theta_A)}$. Rearranging gives (18). This solution can then be used, together with the identity $\widehat{\omega_A} = \widehat{w_A} - \widehat{w_B}$ and equation (17), to derive $\widehat{w_B} = \frac{1}{N-1}a\widehat{(1-\theta_A)}$. Marginal changes in prices, $\frac{dp_j}{d\theta_j}$ and $\frac{dp_i}{d\theta_j}$, follow by noting that from (5) we have $\widehat{p_A} = \beta\widehat{w_A} - \widehat{(1-\theta_A)}$ and $\widehat{p_B} = \beta\widehat{w_B}$. This completes the proof.

Result 2 *Boomerang mechanism of environmental policy.*
The terms-of-trade effect and the TFP effect are monotonically increasing in the so-called 'intermediate goods multiplier' $\frac{1}{\beta} \in [1, \infty)$.

Proof Inspection of $\frac{dw_j}{d\theta_j}$ in (18) immediately shows that the TFP coefficient is proportional to $1/\beta$. With respect to the terms-of-trade coefficient a, differentiation shows that $\frac{da}{d(1/\beta)} = \frac{a}{1/\beta}\left(1+\beta\frac{\varepsilon-1}{1+\beta(\varepsilon-1)}\right) > 0$. This completes the proof.

Result 3 *Desensitization of pollution with respect to local environmental policy.*
Under decentralization ($N \uparrow$):
(i) pollution in any given country becomes less responsive to local environmental policy ($\frac{d\varepsilon_{z,\theta}}{dN} < 0$ and $\frac{d\varepsilon^l_{z,\theta}}{dN} < 0$).
(ii) the responsiveness of global pollution is (strictly) negative ($\frac{d(\varepsilon_{z,\theta}+\phi(N-1)\varepsilon^l_{z,\theta})}{dN} = -(1-\phi)(1-\beta)\frac{da}{dN} \leq 0$).
An increase in the degree of vertical integration ($\beta \downarrow$):
(iii) increases the responsiveness of pollution in any given country to local environmental policy ($\frac{d\varepsilon_{z,\theta}}{d\beta} < 0$ and $\frac{d\varepsilon^l_{z,\theta}}{d\beta} < 0$).

Proof Total differentiation of $\varepsilon_{z,\theta}$ and $\varepsilon^l_{z,\theta}$ with respect to N shows us $\frac{d\varepsilon_{z,\theta}}{dN} = -(1-\beta)\frac{da}{dN} < 0$ and $\frac{d\varepsilon^l_{z,\theta}}{dN} = -(1-\beta)\frac{1}{N-1}\frac{a}{N} = -\frac{\varepsilon^l_{z,\theta}}{N} < 0$. Using these derivatives one can show that $\frac{d(\varepsilon_{z,\theta}+\phi(N-1)\varepsilon^l_{z,\theta})}{dN} = -(1-\phi)(1-\beta)\frac{da}{dN} \leq 0$. This proofs (i) and (ii). Total differentiation of $\varepsilon_{z,\theta}$ and $\varepsilon^l_{z,\theta}$ with respect to β gives us $\frac{d\varepsilon_{z,\theta}}{d\beta} = \frac{1}{\beta}(a-b) + \frac{(1-\beta)(\varepsilon-1)}{1+\beta(\varepsilon-1)}a < \frac{1}{\beta}(a-b) + (\varepsilon-1)a = -\frac{1}{\beta}\frac{1}{N}b < 0$ and $\frac{d\varepsilon^l_{z,\theta}}{d\beta} = -\frac{a}{N-1} + \frac{1-\beta}{N-1}\frac{da}{d\beta} < 0$. This completes the proof.

Proposition 1 *Under a unilateral marginal increase in the stringency of environmental policy:*
1) pollution is affected by (i) a weak link effect and (ii) a global technology effect. The weak link effect decreases pollution at home but increases pollution abroad. The global technology effect decreases pollution in all countries.
2) pollution is reduced at home, that is, $\frac{dz_j}{d\theta_j} = -\varepsilon_{z,\theta}\frac{z}{1-\theta} < 0$.
3) (carbon) leakage is negative, $\frac{dz_i}{d\theta_j} = -\varepsilon^l_{z,\theta}\frac{z}{1-\theta} < 0$ if and only if $\beta < 1$. There is zero leakage ($\frac{dz_i}{d\theta_j} = 0$) if there is no I-O structure ($\beta = 1$).

Proof (1) Total differentiation of (23) with respect to θ_A leads to

$$\frac{dz_A}{d\theta_A} = z_A\frac{e'(\theta_A)}{e(\theta_A)} - z_A\frac{1}{1-\theta_A} + \underbrace{z_A(1-\beta)\frac{1}{\lambda_A}\frac{d\lambda_A}{d\theta_A}}_{\text{weak link effect A}} + \underbrace{z_A\frac{1-\beta}{\beta}\frac{1}{G}\frac{dG}{d\theta_A}}_{\text{global technology effect}} \tag{31}$$

$$\frac{dz_B}{d\theta_A} = \underbrace{z_B(1-\beta)\frac{1}{\lambda_B}\frac{d\lambda_B}{d\theta_A}}_{\text{weak link effect B}} + \underbrace{z_B\frac{1-\beta}{\beta}\frac{1}{G}\frac{dG}{d\theta_A}}_{\text{global technology effect}} \tag{32}$$

where the last two terms on the right-hand side represent respectively the weak link effect and the global technology effect. Since $\frac{d\lambda_A}{d\theta_A} < 0$, $\frac{d\lambda_B}{d\theta_A} > 0$ and $\frac{dG}{d\theta_A} < 0$ it follows that the weak link effect in country A (B) is negative (positive) whereas the global technology effect is negative. (2) Substitution of $\frac{d\lambda_A}{d\theta_A} = \lambda_A\left(\frac{1}{w_A}\frac{dw_A}{d\theta_A} - \frac{1}{w_A+(N-1)w_B}\left(\frac{dw_A}{d\theta_A} + (N-1)\frac{dw_B}{d\theta_A}\right)\right)$ and
$\frac{dG}{d\theta_A} = n^{\frac{\varepsilon}{\varepsilon-1}}\left(-\lambda_A^{1-\beta} + (1-\theta_A)(1-\beta)\lambda_A^{-\beta}\frac{d\lambda_A}{d\theta_A} + (N-1)(1-\theta_B)(1-\beta)\lambda_B^{-\beta}\frac{d\lambda_B}{d\theta_A}\right)$, using result 1, apply-

ing symmetry and using the definition of $\varepsilon_{z,\theta}$ provides us with $\frac{dz_j}{d\theta_j} = -\varepsilon_{z,\theta}\frac{z}{1-\theta} < 0$. (3) Similar to (2), substitution of $\frac{dG}{d\theta_A}$ and $\frac{d\lambda_B}{d\theta_A} = \lambda_B \left(\frac{1}{w_B}\frac{dw_B}{d\theta_A} - \frac{1}{w_A+(N-1)w_B}\left(\frac{dw_A}{d\theta_A} + (N-1)\frac{dw_B}{d\theta_A} \right) \right)$ into (32), applying symmetry and using the definition of $\varepsilon^l_{z,\theta}$ gives us $\frac{dz_i}{d\theta_j} = -\varepsilon^l_{z,\theta}\frac{z}{1-\theta} < 0$. This completes the proof.

Proposition 2 *(i) Under transboundary pollution ($\phi > 0$) we find $\theta^S \gtreqless \theta^{NC} \Leftrightarrow (N-1)\Omega^B_l(N)\Omega^C(N) \gtreqless a\tau\Omega^B(N)$.*
(ii) Under purely local pollution ($\phi = 0$) we have $\theta^S < \theta^{NC}$.
(iii) There exists a unique $\bar{\phi} \equiv \frac{1}{N-1}\frac{a\varepsilon_{z,\theta}+(a-b)(N-1)\varepsilon^l_{z,\theta}}{-(a-b)(\varepsilon_{z,\theta}+(N-2)\varepsilon^l_{z,\theta})-a\varepsilon^l_{z,\theta}}$ such that $\theta^S \gtreqless \theta^{NC}$ for all $\phi \gtreqless \bar{\phi}$ provided $\bar{\phi} \in (0, 1]$.
Proof (i) Substitution of the coefficients from definition 1 into (29) results in the following expressions for the pollution standard:

$$\theta^{NC} = 1 - \left[\frac{\tau(b-a)}{\eta n(\varepsilon_{z,\theta} + \phi(N-1)\varepsilon^l_{z,\theta})\bar{z}} \right]^{\frac{1}{\Phi}} \tag{33}$$

$$\theta^S = 1 - \left[\frac{1}{\eta n \bar{z}} \frac{\tau b}{\varepsilon_{z,\theta} + \phi(N-1)\varepsilon^l_{z,\theta} + (N-1)\left(\phi(\varepsilon_{z,\theta} + (N-2)\varepsilon^l_{z,\theta}) + \varepsilon^l_{z,\theta} \right)} \right]^{\frac{1}{\Phi}} \tag{34}$$

where $\Phi \equiv \frac{(1-\alpha)\beta+\alpha-\alpha(1-\tau)(1-\sigma)}{\alpha\beta} > 0$. Comparing these solutions shows us that $\theta^S \gtreqless \theta^{NC} \Leftrightarrow (N-1)\Omega^B_l(N)\Omega^C(N) \gtreqless a\tau\Omega^B(N)$. (ii) If there are no spillovers the expression for the standard in social optimum from (34) reads $\theta^S|_{\phi=0} = 1 - \left[\frac{1}{\eta n\bar{z}} \frac{\tau b}{\varepsilon_{z,\theta}+2(N-1)\varepsilon^l_{z,\theta}} \right]^{\frac{1}{\Phi}}$. Quick inspection of θ^S and θ^{NC} some rearrangement reveals that $\theta^S < \theta^{NC} \Leftrightarrow -(a-b)(N-1)\varepsilon^l_{z,\theta} < a\varepsilon_{z,\theta} \Leftrightarrow 0 < \frac{1}{\alpha}$. (iii) From (i) we find that $\bar{\phi}$ is implicitly defined by $\theta^S = \theta^{NC}$. Rearranging leads to an explicit expression, $\bar{\phi} \equiv \frac{1}{N-1}\frac{a\varepsilon_{z,\theta}+(a-b)(N-1)\varepsilon^l_{z,\theta}}{-(a-b)(\varepsilon_{z,\theta}+(N-2)\varepsilon^l_{z,\theta})-a\varepsilon^l_{z,\theta}}$.

Proposition 3 *For $\phi < (>)\bar{\phi}$ we find that green welfare is higher (lower) in the non-cooperative equilibrium than in the social optimum.*
Proof Since $\theta^S \gtreqless \theta^{NC}$ for $\phi \gtreqless \bar{\phi}$ we have $Z(\theta^S) \gtreqless Z(\theta^{NC})$ for $\phi \gtreqless \bar{\phi}$. This completes the proof.

10.2 Derivation of the Balanced Trade Condition

10.2.1 Direct Method

Three steps are needed. First, using (2) profit maximization in the intermediate goods sector results in:

$$w_j l_{jy} = \beta p_j y_j \quad \text{and} \quad x_{jy} = (1-\beta)p_j y_j \tag{35}$$

Second, profit maximization in the final goods sector gives us $w_j L_{jC} = (1-\tau)I_j$. Using this result, the definition of nominal income $I_j = w_j L = p_{jC}C$ and $L = L_{jy} + L_{jC}$ we obtain

$$n w_j l_{jy} = \tau I_j \tag{36}$$

Combining (35) and (36) then provides us with expressions for l_{jy} and x_{jy} as function of parameters and domestic income, $l_{jy} = \frac{\tau I_j}{n w_j}$ and $x_{jy} = \left(\frac{1-\beta}{\beta}\right)\frac{\tau I_j}{n}$, as well as being able to rewrite $\sum_{j=1}^{j=N} n p_j q_j =$

$\sum_{j=1}^{j=N} \frac{\tau}{\beta} I_j = \frac{\tau}{\beta} I^w$. Third, we then substitute $l_{jy} = \frac{\tau I_j}{n w_j}$ and $x_{jy} = \left(\frac{1-\beta}{\beta}\right) \frac{\tau I_j}{n}$ into $q_j = (1-\theta_j)(l_{jy})^{\beta}(x_{jy})^{1-\beta}$, which in turn we substitute for q_j on the left-hand side of the demand function (10) and finally we rearrange to get:

$$I_j = n\left(p_j\right)^{1-\varepsilon} I^w$$

which equals (11) in the main text.

10.2.2 Alternative Method

From a trade theory point of view, a more intuitive method of deriving the BoT condition is by equating imports and exports. Let use the abbreviations IM_j and EX_j to refer to imports and exports of intermediate goods by country j respectively. With n intermediates produced by each country and a total number of $N-1$ trading partners, imports and exports are defined as:

$$\begin{aligned} IM_j &= n(p_1 y_{1j} + p_2 y_{2j} + ... + p_{j-1} y_{j-1,j} + p_{j+1} y_{j+1,j} + ... + p_N y_{Nj}) && (37) \\ &= \sum_i n p_i y_{ij} - n p_j y_{jj} && (38) \end{aligned}$$

$$\begin{aligned} EX_j &= n(p_j y_{j1} + p_j y_{j2} + ... + p_j y_{j,j-1} + p_j y_{j,j+1} + ... + p_j y_{jN}) && (39) \\ &= n p_j y_j - n p_j y_{jj} && (40) \end{aligned}$$

In (38) we can substitute for $\sum_i n p_i y_{ij} = \frac{\tau}{\beta} I_j$ and $n p_j y_{jj} = \frac{\tau}{\beta} I_j \frac{I_j}{I^w}$:

$$IM_j = \frac{\tau}{\beta} I_j \left(1 - \frac{I_j}{I^w}\right) \tag{41}$$

whereas in (40) we can substitute for $n p_j y_j = n p_j^{1-\varepsilon} \frac{\tau}{\beta} I^w$ and $n p_j y_{jj} = n p_j y_j \frac{X_j}{X^w} = n p_j^{1-\varepsilon} \frac{\tau}{\beta} I_j$:

$$EX_j = n p_j^{1-\varepsilon} \frac{\tau}{\beta} \left(1 - \frac{I_j}{I^w}\right) I^w \tag{42}$$

Equating imports and export results in the equation obtained in the main text, $I_j = n p_j^{1-\varepsilon} I^w$. Equating imports (41) and exports (42) then leads to the balanced trade condition:

$$I_j = n {p_j}^{1-\varepsilon} I^w \tag{43}$$

where we divided by the import (export) ratio $\frac{IM_j}{I_j} = \frac{EX_j}{I_j} = \frac{\tau}{\beta}\left(1 - \frac{I_j}{I^w}\right)$ on both sides of the equation. Thus, the left-hand side and right-hand side of (43) represent respectively imports and exports divided by the import ratio. Under balanced trade the import ratio is half the trade intensity, which equals $v_j \equiv \frac{EX_j + IM_j}{I_j} = 2\frac{\tau}{\beta}\left(1 - \frac{I_j}{I^w}\right)$. With symmetric countries it then follows immediately that $v = 2\frac{N-1}{N}\frac{\tau}{\beta}$. Acemoglu and Ventura (2002) obtain $v = 2\tau$, which can be obtained as a special case in our model when $\beta = 1$ (no I-O structure) and $N \to \infty$[15].

[15]Similarly, "openness" in our setting equals $\frac{N-1}{N}\frac{\tau}{\beta}$ instead of τ in the model by Acemoglu & Ventura (2002).