Trade, Leakage and Consumption-based EKC

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Abstract

A substantial fraction of the growth in the developing countries satisfies the consumption in developed countries. We consider a two-country North-South open economy model à la Andreoni and Levinson (2001) in which production is accompanied with emission of a global pollutant, say, GHG. Assume that the North has a clean but expensive production technology relative to the South. It is then plausible that North’s Environmental Kuznets Curve (EKC) is inverted U-shaped from producer’s account but both regions’ EKC are monotonically increasing from consumer’s account. The association between leakage and decoupling is established. A contribution of this paper to the theory of international trade is that optimal trade may arise from the tradeoff between private good consumption, tragedy of commons, and public good provision. Trade occurs even if private consumption goods are homogenous and exhibits constant returns to scale.

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1 Introduction

Between 2000 and 2008, global GHG emissions grew at a rate of 3.4% per year, a marked increase from the rate of 1.0% per year throughout the 1990s. The emission from combustion of fossil fuels was 1.3% lower in 2009 than 2008 due to global economic recession, but it was less than half the drop that was predicted. This was because, while economies in developed countries were down, activity in the developing world was rising. The reductions in the developed countries were offset by steady growth in countries like China, which increased emissions by 8% in 2009. Emissions increased again to 3% in 2010. At the same time, carbon intensity, which is the amount of CO$_2$ released per unit of GDP, improved very slowly.

In 2009, carbon intensity in the OECD countries reduced by 2.9% and amounted to 0.33 kCO2/$05p in the OECD countries$^1$. Carbon intensity continued to be higher in non-OECD countries. For world’s largest emitter, despite a slight improvement, China continued to post a high carbon intensity (0.81 kCO2/$05p$).

At the 67th annual meeting of the American Economic Association in 1954, Simon Kuznets delivered the presidential address “Economic Growth and Income Inequality” and suggested that, as per capita income increases, income inequality also increases at first but then, after some turning point, starts declining (Kuznets, 1955, pp.23–24). This changing relationship between per capita income and income inequality can be represented by an inverted-U-shaped curve, known as the Kuznets curve, for which Kuznets was awarded the Nobel prize in economics in 1971. The Kuznets curve hypothesis posits that initially,

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at lower levels of per capita income, income distribution is skewed toward higher income levels so that income inequality is high. As income rises, skewness is reduced and income inequality becomes lower.

The environmental Kuznets curve (EKC for short, as coined by Panayotou, 1993) is referred to as the hypothesis that the relationship between environmental degradation and per capita income exhibits an inverted-U shape. The logic of the EKC relationship is rather intuitive. In early stages of industrialization, pollution grows rapidly because high priority is given to increasing material output, and people are more interested in income than environment. In the later stage, however, as income rises, the willingness to pay for a clean environment increases by a greater proportion than income, regulatory institutions become more effective for the environment, and pollution level starts declining.

The inverted-U relationship reveals that economic growth could be compatible with environmental improvement. The primary motivation for empirical studies on the EKC is to search for evidence of a link between income and environmental quality, so as to answer the relevant question of whether economic growth can be apart of the solution for environmental problems. Since the early 1990s, heated debates have been made on the EKC hypothesis, and plenty of empirical studies support the inverted-U relationship. The reader is referred to, e.g., Borghesi (2001), Dinda (2004), He (2007) for overviews and comparisons on the EKC.

Research and Development (R&D) is accompanied with economic growth hence production processes become less pollution intensive. At the same time, because direct production costs such as labor costs are lower in developing countries, developed countries tend to export less and import more dirty products\footnote{We assume here that pollutants are emitted during production process, not in consumption.}. A plausible scenario is that instead of achieving a global emission reduction, emissions are displaced abroad, causing the notorious leakage problem. Hence the observed, or projected inverted U-shaped EKC in developed countries can be misleading. This so-called “decoupling”, which refers to the case that emissions grow at a lower rate than does income, then conceals the fact that emissions may be displaced abroad and total emissions grow at the same or even faster pace than income.
Stern (2004), in his well-known survey, calls for empirical analyses on how international trade relates EKC. There are several existing papers respond to this. For instance, Fæhn and Bruvoll (2009) investigate the pollution leakage hypothesis using Norwegian data between 1980 and 2000 and report a mixed message but basically reject the hypothesis of a positive relationship between decoupling and leakage. First, it is found that contrary to the initial premise, emission leakages fell in this period. The decoupling in recent decades coincide with decreasing emission leakage. Their second finding from the projection of CGE computation rejects the pollution leakage hypothesis, i.e., decoupling will grow weaker while leakage increases. Muradian et al (2002), using data from 1976 to 1994, discover a positive relationship between economic growth and embodied emissions in net imports.

Antweiler (1996) proposes the term “pollution terms of trade” or “environmental terms of trade”, defined as the ratio of the pollution content by unit of monetary exports relative to the pollution content by unit of import, as a measure of whether a country gains or loses from trade environmentally. He finds, using input-output analysis for the year 1987, that the exports of developed countries are more pollution-intensive than are their imports, and the opposite holds for developing countries. Suri and Chapman (1998), and Friedl and Getzner (2003) find that increasing imports is an important factor for reduced emissions in developed countries. Wyckoff and Roop (1994) use a monetary input-output analysis and emissions data to estimate the amount of CO$_2$ emissions embodied in the imports of manufactured goods in six of the largest OECD countries and their findings reveal that about 13% of total emissions is embodied in manufactured imports.

Weber and Peters (2009) examine the effect of introducing carbon tariffs as a means to curb the flow of embodied carbon. Others (e.g., Peters and Hertwich 2008, Guan et al, 2009) argue that if nations who import more embodied carbon than export can assume more responsibility for global emissions, the exporting countries (mainly China among other large emerging economies) may be willing to be more cooperative in climate commitments.

Despite these well observed facts and the calls for analyses (e.g., Stern (2004)), few attempts in theoretically modelling pollution leakage and decoupling were made in the existing literature. In particular, none of these studies answers the question that if pollution
accompanied with production is global, why would some countries displace production to overseas at the first place?

We investigate the relationship between decoupling and leakage in a theoretical framework following Andreoni and Levinson (2001). The purpose is to examine the incentives and tradeoffs of leakage since when pollutant is global, it is not clear in a theoretical basis, why would a country relocate its production overseas either by importation from another country’s exporters or physical relocation of its own firms\footnote{In the latter case, it is often referred to the “Pollution Haven Hypothesis” with a separate body of literature (e.g., Jaffe et al., 1995; Porter and van der Linde, 1995; Copeland and Taylor, 2004; Levinson and Taylor, 2008).}. In particular, what are the motives and consequences of such ‘ecological unequal’ exchange\footnote{When the emissions embodied in A’s imports from ‘B’ are larger than in B’s imports from ‘A’. If region ‘B’ faces ‘deteriorating’ ETT over time with region ‘A’, we can say that there is a trend towards ecologically unequal exchange between the two areas.} when pollution is displaced to a country’s trade-partner. This pollution displacement is also called “peripheralization” (Belowers and Leroy, 1994) in the literature. Although the peripheralization of environment-intensive activities from rich to poor countries associated with trade is empirically identified and supported, a formal theoretical model is lack.

The current paper establishes a simple theoretical model to characterize the decoupling and leakage effects, then computes the consumption-based carbon dioxide emissions using input-output approach, and finally estimates the consumption-based EKCs. The per unit pollution affects all countries in the same magnitude, in the case of global pollutant. But the income/consumption transfer and savings due to production cost differentials and emission externality (measured by the incremental quantity of emissions caused by misaligned incentives) may be considered strategically.

There is a somewhat separate body of literature on consumption-based accounting of emissions and resources (CBA) using input-output models. This strand of studies addresses the producer versus consumer responsibility for emissions from the earlier papers (e.g., Eder and Narodoslawsky, 1999; Munksgaard and Pedersen, 2001). With heated debates on responsibility sharing in the international political arena such as the Copenhagen summit, the
question gained renewed interest (Andrew and Forgie, 2008; Lenzen et al., 2007; Rodrigues and Domingos, 2008; Weber and Peters, 2009).

The second part of the paper quantifies the embodied emissions in trade from producers’ and consumers’ accounts using GTAP database in a multi-regional input-output model (MRIO). We then run simple cross section and panel regressions using the results we calculated from the input-output model, and compare them to the EKCs estimated by econometric models using World Bank data. Our MRIO results show that consumption-based EKC may not be inverted U-shaped, rather a linearly increasing function thus negating the EKC hypothesis.

The rest of the paper is organized as follows. Section 2 introduces the theoretical model and characterizes the equilibrium, section 3 offers a MRIO analysis and quantification of consumption-based emissions, section 4 presents various econometric estimation results, and section 3 concludes the paper.

2 The Theoretical Model

There are at least four logics implied by the inverted-U shape EKC in the literature. The most common explanation is that citizens of a rich country assign higher value to environmental amenities (Pezzey, 1992; Selden and Song, 1994; Baldwin, 1995). Hence, demand for environment increases as income reaches a certain level. The second explanation refers to the structural change problem: when an economy evolves from agricultural to industrial, energy intensity and total emissions increase but when it changes from heavy industry to services and innovation based industry as GDP grows, emissions start to fall (Grossman and Krueger, 1993). Third, a wealthier nation can afford more R&D on cleaner technology than its poor counterparts (Komen et al., 1997). Fourth, environmental friendly policies may gain more political support when a nation is sufficiently rich (e.g., Ng and Wang, 1993).

Despite the optimistic message delivered by EKC hypothesis, there is a surge of emissions since 2000 which has been driven not only by growth of the world population and
per-capita GDP, but also by unanticipated global increases in the energy intensity of GDP and the carbon intensity of energy. In particular, export growth in a few large emerging economies such as China has contributed to this surge. A substantial fraction of the exports in these countries satisfies the consumption in developed trading partners. This leads to the concerns of leakage or embodied emissions in trade, and the overlooked relationship between decoupling and leakage. Recent studies in attempts to quantifying the emissions embodied in trade justified this claim.

Having observed that rich countries displace some of their CO$_2$ emissions to poor countries via international trade with embodied emissions, all the above listed explanations suffer from the fact that what is the purpose of displacing emissions when the pollutant is transboundary? Furthermore, if the embodied emissions from imports are sufficiently high, will the inverted U-shape hypothesis still be valid? For the first question, there are several tradeoffs: when a rich country imports from its poor trading partner, the former saves production costs since the latter is usually endowed with abundant cheap labor and/or natural resources (primary resources), but at the same time pollution is worsened as the poor country gains from trade and expands output for its own consumption. On the other hand, the rich country can spend the savings from the imports on pollution abatement which may (partially) offset the emissions although the poor country free rides on such abatement.

Regarding the shape of EKC, if the inverted U-shape holds for a closed economy model, then once opening up to trade, global EKC may not be invertedly U-shaped anymore: the exporting country (developing country) may over-emit than what one-country model predicts since it free rides on the abatement efforts by the developed country. Such tradeoffs, although not very difficult to articulate, they are never found in the existing literature, to the best of our knowledge.

The best known theoretical papers on EKC include McConnell (1997) and Andreoni and Levinson (2001). The former establishes the inverted-U shape EKC through the role of income elasticity of demand for environmental quality when income can be divided to consumption and abatement. Lieb (2002) extends the model of McConnell (1997) by
introducing a corner solution when income is low, and shows that the necessary condition for EKC is that the environmental quality is a normal good. The main pitfall of McConnell (1997) is that no close form utility functions are imposed hence the model is very difficult to extend to a setting that incorporates trade. The current paper uses the setup in Andreoni and Levinson (2001) and extends to a two country trade setting.

2.1 Model Setup

The model setup is similar with Andreoni and Levinson (2001, J. Pub. Econ.) except two country setting and the introduction of international trade. Formally, assume that there are two countries, the North \(i = 1\) and the South \(i = 2\). There is only one homogeneous consumption goods whose production cost is 1 in the South and \(\theta\) in the North where \(\theta > 1\). For simplicity, assume that there is no trade cost and no intermediation for trade. Denote \(\theta'\) as the trading price and naturally \(\theta' \in (1, \theta)\). In this section, we suppose that production costs are different for the two players, or the prices of consumption good are different. Emissions are accompanied with production only\(^5\).

The utility function of a country is given by

\[
U = X_i - P,
\]

where \(P\) is the pollution level which is a function of consumption \(X_i\) and the abatement effort \(E\). The pollution is perfectly transboundary and its relationship with world’s total consumption and abatement efforts is given by

\[
P = C - C^\alpha E^\beta, \quad \alpha, \beta > 0.
\]

Income can be only used for consumption and abatement. Thus the resource constraints for the two countries with the presence of trade are

\[
M_1 = \theta C_1 + \theta' I + E_1, \quad C_1, I, E_1 \geq 0, \quad (1)
\]

\[
M_2 + (\theta' - 1) I = C_2 + E_2, \quad C_2, E_2 \geq 0. \quad (2)
\]

\(^5\)Hence as far as emissions are concerned for consumption, they are simply embodied.
where the total output in the North is $C_1$ and the consumption is $X_1 = C_1 + I$ where $I$ is the imports; and the corresponding output and consumption in the South are respectively $C_2 + I$ and $X_2 = C_2$. The world’s total consumption is $C = C_1 + C_2 + I$ and total efforts on abatement is $E = E_1 + E_2$. The North’s utility is $U_1 = (C_1 + I) - P$ and the South’s is $U_2 = C_2 - P$.

Because the South gains from its exports, it will increase its consumption. Knowing this would occur with certainty, the North strategically chooses import $I$ upfront. In order to apply backward induction, consider a dynamic game where the North chooses the quantity of imports first, and then the South decides how much to produce and how much efforts on abatement.

The maximization problem of the South is written as

$$
\max_{C_2, E_2} \quad U_2 = C_2 - P = C^\alpha E^\beta - C_1 - I
$$

s.t. (2).

The corresponding Lagrangian can be written as

$$
L_2 = C^\alpha E^\beta - C_1 - I + \lambda_2 (M_2 + (\theta' - 1) I - C_2 - E_2),
$$

where $\lambda_2 > 0$ because the utility is increasing in budget. The Kuhn-Tucker conditions are

$$
\frac{\partial L_2}{\partial C_2} = \alpha C^{\alpha - 1} E^\beta - \lambda_2 \leq 0, \text{ with } C_2 \frac{\partial L_2}{\partial C_2} = 0;
$$

$$
\frac{\partial L_2}{\partial E_2} = \beta C^\alpha E^{\beta - 1} - \lambda_2 \leq 0, \text{ with } E_2 \frac{\partial L_2}{\partial E_2} = 0.
$$

Similarly, the North’s maximization objective is

$$
\max_{C_1, E_1} \quad U_1 = C_1 + I - P = C^\alpha E^\beta - C_2
$$

s.t. (1).

where $\lambda_1 > 0$ and the corresponding first order conditions are:

$$
\frac{\partial L_1}{\partial C_1} = \alpha C^{\alpha - 1} E^\beta - \lambda_1 \theta \leq 0, \text{ with } C_1 \frac{\partial L_1}{\partial C_1} = 0;
$$

$$
\frac{\partial L_1}{\partial E_1} = \beta C^\alpha E^{\beta - 1} - \lambda_1 \leq 0, \text{ with } E_1 \frac{\partial L_1}{\partial E_1} = 0.
$$
Record the solution to (6) as

\[ C_1^* = C_1(M_1, M_2, \theta, \theta', I), \]  
\[ E_1^* = E_1(M_1, M_2, \theta, \theta', I); \]  
\[ C_2^* = C_2(M_1, M_2, \theta, \theta', I), \]  
\[ E_2^* = E_2(M_1, M_2, \theta, \theta', I). \]  

Because \( \theta > 1 \), we immediately arrive to the following lemma.

**Lemma 1** The equilibrium solution to (6) and (3) is a corner solution, i.e., \( C_1^*E_1^*C_2^*E_2^* = 0 \).

**Proof.** It can be proven by contradiction. Suppose that the equilibrium solution is an interior solution, i.e., \( C_1^*, E_1^*, C_2^*, E_2^* > 0 \). Thus according to the complementary slack conditions, conditions, (4), (5), (7) and (8) must all hold in equality. But this is in contradiction of the assumption that \( \theta > 1 \). Therefore, at least one of the four variables in \( C_1^*, E_1^*, C_2^*, E_2^* \) must be zero. \( \blacksquare \)

Next, we discuss the equilibria in different scenarios and the conditions.

### 2.2 Case I. North sufficiently rich

This case corresponds to the parameter constraints obtained by Kuhn-Tucker conditions, i.e., \( 0 < \lambda_2 = \theta \lambda_1 \) from which (5) holds with strict inequality where \( E_2 = 0 \), and \( E_1, C_1, C_2 > 0 \). From the maximization, we then obtain:

\[ C_1 = \frac{\alpha(M_1 - \theta'I) - \beta \theta(M_2 + \theta'I)}{(\alpha + \beta)\theta}, \]
\[ E_1 = \frac{\beta(M_1 - \theta'I) + \beta \theta(M_2 + \theta'I)}{\alpha + \beta}, \]
\[ C_2 = M_2 + (\theta' - 1)I. \]

By (13), a necessary condition for \( C_1 > 0 \) is \( \alpha M_1 > \theta \beta M_2 \). (13) also implies that \( \frac{\partial C_1}{\partial \theta} = \frac{\alpha + \beta \theta \frac{\partial}{\partial \theta}}{\alpha + \beta} < -\frac{\partial}{\partial \theta} \).
Rewrite the North’s utility as a function of $I$:

$$U_1 = \frac{\alpha \beta}{(\alpha + \beta)^{\alpha + \beta}}(\theta(M_2 + \theta'I) + (M_1 - \theta'I))^{\alpha + \beta} - (M_2 + (\theta' - 1)I). \quad (16)$$

Denote the first derivative of $U_1$ with respect to import as $\dot{H}(I) \equiv \frac{dU_1}{dI}$. Since $U_1$ is concave in $I$ if $\alpha + \beta < 1$, then when (17) and (18) hold, there exists a unique solution $\hat{I}^* \in (0, M_1/\theta')$ such that $\dot{H}(\hat{I}^*) = 0$.

Differentiating $\dot{H}(\hat{I}^*) = 0$ yields

$$\frac{d\hat{I}^*}{d\theta'} = -\frac{\partial \dot{H}/\partial \theta'}{\partial \dot{H}/\partial I} \Rightarrow \text{sign} \frac{d\hat{I}^*}{d\theta'} = \text{sign} \frac{\partial \dot{H}}{\partial \theta'}$$

$$\frac{\partial \dot{H}}{\partial \theta'} = \frac{\alpha \beta}{(\alpha + \beta)^{\alpha + \beta - 1}}(\theta(M_2 + \theta'I) + (M_1 - \theta'I))^{\alpha + \beta - 1}(\theta - 1) - 1$$

$$\quad + (\alpha + \beta - 1)(\alpha + \beta)^{\alpha + \beta - 1}(\theta(M_2 + \theta'I) + (M_1 - \theta'I))^{\alpha + \beta - 2}(\theta - 1)^2\hat{I}^*\theta'.$$

The first order condition $\dot{H}(\hat{I}^*) = 0$ yields that $\frac{\alpha \beta}{(\alpha + \beta)^{\alpha + \beta - 1}}(\theta(M_2 + \theta'I) + (M_1 - \theta'I))^{\alpha + \beta - 1}(\theta - 1) = \frac{\theta' - 1}{\theta'}$ which implies that $\frac{\partial \dot{H}}{\partial \theta'} < 0$. Thus $\frac{d\hat{I}^*}{d\theta'} < 0$. We summarize the results in the following proposition.

**Proposition 1** If $\alpha + \beta < 1$, and $\alpha M_1 > \theta \beta M_2$, when (17) and (18) hold, the North imports from the South. The equilibrium trade volume is $\hat{I}^* \in (1, M_1/\theta')$ and it decreases in $\theta'$.

**Proof.** Notice that the first and second derivatives of (16) are respectively,

$$\frac{dU_1}{dI} = \frac{\alpha \beta}{(\alpha + \beta)^{\alpha + \beta - 1}}(\theta(M_2 + \theta'I) + (M_1 - \theta'I))^{\alpha + \beta - 1}(\theta - 1)\theta' - (\theta' - 1)$$

and $$\frac{d^2U_1}{dI^2} = (\alpha + \beta - 1)\frac{\alpha \beta}{(\alpha + \beta)^{\alpha + \beta - 1}}(\theta(M_2 + \theta'I) + (M_1 - \theta'I))^{\alpha + \beta - 2}((\theta - 1)\theta')^2.$$

If $\alpha + \beta < 1$, $U_1$ is a concave function of $I$. An interior solution exists if $\frac{d\hat{I}^*}{d\theta'}|_{I=0} > 0 >$
\[ \frac{d\ell_t}{d\theta} \big|_{I=M_t/\theta'} \text{ which can be written as} \]
\[ \frac{\alpha^a \beta^b}{(\alpha + \beta)^{a+b-1}} (\theta(M_2 + M_1))^{\alpha+b-1}(\theta - 1)\theta' - (\theta' - 1) < 0, \tag{17} \]
\[ \frac{\alpha^a \beta^b}{(\alpha + \beta)^{a+b-1}} (\theta M_2 + M_1)^{\alpha+b-1}(\theta - 1)\theta' - (\theta' - 1) > 0. \tag{18} \]

In this case, world’s total consumption and abatement efforts are
\[ C = \frac{\alpha}{\alpha + \beta} (\theta(M_2 + \theta' I) + (M_1 - \theta' I)) \text{ and } E = \frac{\beta}{\alpha + \beta} (\theta(M_2 + \theta' I) + (M_1 - \theta' I)) \]
respectively.

We also present some comparative statics for consumptions in both countries and abatement in the North with respect to trade price. It can be shown that
\[ \frac{dC_1}{d\theta'} = \frac{\partial C_1}{\partial I^*} \frac{dI^*}{d\theta'} + \frac{\partial C_1}{\partial \theta'} \frac{d\theta'}{<0}, \text{ the sign is undetermined;} \]
\[ \frac{dE_1}{d\theta'} = \frac{\partial E_1}{\partial I^*} \frac{dI^*}{d\theta'} + \frac{\partial E_1}{\partial \theta'} \frac{d\theta'}{<0}, \text{ the sign is undetermined;} \]
\[ \frac{dC_2}{d\theta'} = (\theta' - 1) \frac{dI^*}{d\theta'} + \hat{I}^* (\frac{1}{\theta'} - \varepsilon_1 \theta' + 1) > 0 \text{ if } \varepsilon_1 \theta' < \frac{\theta'}{\theta' - 1}, \]

where\[ \varepsilon_1 \theta' \equiv -\frac{dI^*}{d\theta'} \frac{\theta'}{I^*}. \]

Thus the signs of \( \frac{dC_1}{d\theta'}, \frac{dE_1}{d\theta'}, \text{ and } \frac{dC_2}{d\theta'} \) are all undetermined. The indeterminacy of \( \frac{dC_2}{d\theta'} \) comes from the crowding-out effect (the incremental domestic production in response to an import price increase, measured by \( \frac{\partial C_1}{\partial I^*} \cdot \frac{dI^*}{d\theta'} \)), and terms-of-trade effect on domestic output (domestic production’s direct response to import price, measured by \( \frac{\partial C_1}{\partial \theta'} \)), which have opposite directions. Note that these effects are implied by social welfare maximization and in our case, similar to Andreoni and Levinson (2001), there is no firm or the weight to the firm is simply zero.

Similarly, the indeterminacy of \( \frac{dE_1}{d\theta'} \) also comes from two effects with opposite signs, i.e., indirect effect of terms of trade on domestic abatement (measured by \( \frac{\partial E_1}{\partial I^*} \cdot \frac{dI^*}{d\theta'} \)), and the direct effect of terms of trade on domestic abatement (measured by \( \frac{\partial E_1}{\partial \theta'} \)). The intuition for the former one is that when an increase of import price adversely affects the import
volume, abatement should decrease since more domestic resource should be procured for consumption goods. The intuition for the latter is that additional domestic resources should be given to abatement since imports decrease due to worsened terms of trade.

Finally, if $\alpha + \beta = 1$, $U_1 = \alpha^{\alpha} \beta^{\beta} (\theta(M_2 + \theta' I) + (M_1 - \theta' I)) - (M_2 + (\theta' - 1) I)$, the only case for an interior solution to exist is that $\alpha^{\alpha} \beta^{\beta} (\theta - 1) \theta' - (\theta' - 1) = 0$ holds.

### 2.3 Case II. North relatively rich

In this case, we have $0 < \lambda_1 < \lambda_2 < \theta \lambda_1$. Hence (5) and (7) hold with strict inequalities. By the complementary slack conditions, $C_1 = E_2 = 0$. Because utility functions monotonically increase in the budgets, hence $E_1, C_2 > 0$ and $E_1 = M_1 - \theta' I, C_2 = M_2 + (\theta' - 1) I$. From the complementary slack conditions, it can be shown that $\lambda_1 = \beta C^\alpha E^{\beta - 1}$, and $\lambda_2 = \alpha C^{\alpha - 1} E^\beta$.

World’s total consumption and abatement inputs are respectively $C = M_2 + \theta' I$, and $E = M_1 - \theta' I$.

Note that the condition $0 < \lambda_1 < \lambda_2 < \theta \lambda_1$ is equivalent to

$$1 < \frac{\alpha(M_1 - \theta' I)}{\beta(M_2 + \theta' I)} < \theta,$$

in which a necessary condition is $\alpha M_1 > \beta M_2$.

The utility in the North can be written as

$$U_1 = C^\alpha E^\beta - C_2 = (M_2 + \theta' I)^\alpha (M_1 - \theta' I)^\beta - (M_2 + (\theta' - 1) I).$$

(20)

The first derivative of $U_1$ with respect to $I$ is

$$H(I) \equiv \frac{dU_1}{dI} = (M_2 + \theta' I)^{\alpha - 1} (M_1 - \theta' I)^{\beta - 1} \left( \alpha(M_1 - \theta' I) - \beta(M_2 + \theta' I) \right) - (\theta' - 1).$$

(21)

If $\alpha + \beta \leq 1$, we show that $H' < 0$ in the Appendix, or $U_1$ is concave on $I$. The sufficient condition for a unique interior solution $I^* \in (0, M_1 / \theta')$ such that (20) is maximized, i.e., $H(I^*) = 0$, and

$$\theta' \left( M_1^{\beta - 1} M_2^{\alpha - 1} (\alpha M_1 - \beta M_2) - 1 \right) + 1 > 0.$$

(22)

We summarize the result in the following proposition whose proof is omitted.
Proposition 2 When (22) holds with $\alpha + \beta \leq 1$ and $\alpha M_1 \geq \beta M_2$, there exists a unique equilibrium in which

\[ C_1 = 0, \quad E_1 = M_1 - \theta' I^*; \quad E_2 = 0, \quad \text{and} \quad C_2 = M_2 + (\theta' - 1) I^*, \]

where trade volume $I^* \in (0, M_1/\theta')$ is uniquely determined by

\[ (M_2 + \theta'I)^{\alpha-1} (M_1 - \theta'I)^{\beta-1} (\alpha(M_1 - \theta'I) - \beta(M_2 + \theta'I)) - (\theta' - 1) = 0. \]

There are other cases where $0 < \lambda_2 < \lambda_1$, or $0 < \lambda_2 = \lambda_1$, or $0 < \theta \lambda_1 < \lambda_2$. We show in the appendix that these do not arise in equilibrium. Therefore these off-equilibrium cases are omitted in the text.

2.4 Case III. North relatively poor

In this case, $0 < \lambda_2 < \lambda_1$, (7) and (8) hold in strict inequalities, and according to the complementary slack conditions, $C_1 = E_1 = 0$. Note since the utility functions are strictly increasing in total abatement efforts, total abatement can not be 0, hence $E_2 \neq 0$.

Then the first subcase here is $C_2 = 0 < E_2$ and the complementary slack conditions are $\lambda_2 = \beta C^\alpha E^{\beta-1} > \alpha C^{\alpha-1} E^\beta$. From the resource constraints, we know that $E_2 = M_2 + (\theta' - 1) I$, hence the world total consumption and abatement are respectively $C = I$, and $E = M_2 + (\theta' - 1) I$. However this case does not arise in equilibrium. The proof is provided in appendix.

The second subcase is when $C_2 > 0$, $E_2 > 0$, and the corresponding complementary slack condition is $\lambda_2 = \beta C^\alpha E^{\beta-1} = \alpha C^{\alpha-1} E^\beta$. From the resource constraints, we obtain

\[ C_2 = \frac{\alpha}{\alpha + \beta} (M_2 + \theta'I) - I, \quad (23) \]
\[ E_2 = \frac{\beta}{\alpha + \beta} (M_2 + \theta'I). \quad (24) \]

The utility of the North in this subcase is then

\[ U_1 = C^\alpha E^\beta - C_2 = \frac{\alpha^\beta}{(\alpha + \beta)^{\alpha + \beta}} (M_2 + \theta'I)^{\alpha + \beta} - \left( \frac{\alpha}{\alpha + \beta} (M_2 + \theta'I) - I \right). \]
To be consistent with $C_1 = E_1 = 0$, it is required that $\frac{dU_1}{dI} > 0$. Notice that

$$\frac{dU_1}{dI} = \frac{\alpha^\alpha \beta^\beta}{(\alpha + \beta)^{\alpha+\beta-1}} (M_2 + \theta' I)^{\alpha+\beta-1} \theta' - \frac{\alpha}{\alpha + \beta} \theta' + 1,$$

then if $\theta' < \frac{\alpha+\beta}{\alpha}$, for all $I > 0$, $\frac{dU_1}{dI} > 0$ holds. In equilibrium, $I^* = M_1/\theta'$. Finally we verify that $C_2 \geq 0$, i.e., (23) is nonnegative. This is equivalent to $\alpha \theta' M_2 \geq (\beta - \alpha(\theta' - 1))M_1$.

Next we verify that the condition is consistent with $1 < \lambda_2 < \lambda_1$. In this case, note that $I = M_1/\theta'$, $C = \frac{\alpha}{\alpha + \beta} (M_1 + M_2)$, and $E = \frac{\beta}{\alpha + \beta} (M_1 + M_2)$. The equilibrium utility levels are

$$U_1 = \frac{\alpha^\alpha \beta^\beta}{(\alpha + \beta)^{\alpha+\beta}} (M_1 + M_2)^{\alpha+\beta} - \frac{\alpha}{\alpha + \beta} (M_1 + M_2) + \frac{M_1}{\theta'} \quad (25)$$

and

$$U_2 = \frac{\alpha^\alpha \beta^\beta}{(\alpha + \beta)^{\alpha+\beta}} (M_1 + M_2)^{\alpha+\beta} - \frac{M_1}{\theta'}. \quad (26)$$

It can be shown that when $\theta' < \frac{\alpha+\beta}{\alpha}$, $\lambda_1 = \frac{\partial U_1}{\partial M_1} > \lambda_2 = \frac{\partial U_2}{\partial M_2}$. In particular, we can establish:

$$\lambda_1 = \lambda_2 + \frac{1}{\theta'} - \frac{\alpha}{\alpha + \beta} > \lambda_2.$$

We summarize the above results in the following proposition whose proof is omitted.

**Proposition 3** If $\theta' \in (1, \frac{\alpha+\beta}{\alpha})$ and $M_1 < \frac{\alpha \theta'}{\beta - \alpha(\theta' - 1)} M_2$, there is a unique equilibria, where the South exports part of its output and consumes the remainings, and spends the rest of the resources to pollution abatement; the North spends all its resources in imports and spends nil on domestic production and abatement. That is, $C_1 = E_1 = 0$, $I = M_1/\theta'$, $C_2 = \frac{\alpha}{\alpha + \beta} (M_1 + M_2) - M_1/\theta'$, $E_2 = \frac{\beta}{\alpha + \beta} (M_1 + M_2)$.

**Remarks.** From the perspective of South’s optimal reaction to the import by the North, because of the public goods effect of pollution abatement, the imports by the North has two impacts on the South’s consumption. The first is direct substitution effect, and the second is the income effect by the profits from exports, where the ratio for consumption is $\frac{\alpha}{\alpha + \beta}$ and $\theta'$ is the per unit revenue of export. If the income effect is smaller than the
substitution effect, i.e., \( \frac{\alpha}{\alpha + \beta} \theta' < 1 \), the South’s consumption is decreasing in the export. On the other hand, because the South’s abatement level increases due to income effect, world’s total abatement increases. Therefore, the North benefits from the two outcomes, and its utility monotonically increases in imports.

### 2.5 Production-based EKCs

First, define the net pollution for each country as the total emission by production within its sovereignty less its contribution to world emission abatement, i.e.,

\[
P_1 = C_1 - C_{\alpha E_1},
\]

\[
P_2 = C_2 + I - C_{\alpha E_2}.
\]

Now consider case II where import volume is determined by the following:

\[
H(I; M_1, M_2) = (M_2 + \theta' I)^{\alpha-1} (M_1 - \theta' I)^{\beta-1} (\alpha (M_1 - \theta' I) - \beta (M_2 + \theta' I)) - \frac{\theta' - 1}{\theta'} = 0.
\]

It can be shown that \( H \) is a monotonically decreasing function of \( I \), i.e.,

\[
\frac{\partial H}{\partial I} = \theta' (M_2 + \theta' I)^{\alpha-2} (M_1 - \theta' I)^{\beta-2} F(I) < 0
\]

where \( F(I) := \alpha(\alpha - 1)(M_1 - \theta' I)^2 - 2\alpha\beta(M_2 + \theta' I)(M_1 - \theta' I) + \beta(\beta - 1)(M_2 + \theta' I)^2 < 0 \).

We then obtain that

\[
P_1 = -C_{\alpha E_1} = -(U_1 + M_2 + (\theta' - 1)I)
\]

\[
P_2 = M_2 + \theta' I
\]

\[
P = C - C_{\alpha E_2} = P_1 + P_2.
\]

To understand the shape of the EKC, we investigate the import volumes and net pol-
olutions in response to income variations, namely $\frac{I}{M_i}$ and $\frac{P_i}{M_i}$. They are:

$$
\begin{align*}
\frac{\partial H}{\partial M_1} &= \alpha \beta (M_2 + \theta' I)^{\alpha-1}(M_1 - \theta' I)^{\beta-1} - \beta(\beta - 1)(M_2 + \theta' I)^{\alpha}(M_1 - \theta' I)^{\beta-2} > 0, \\
\Rightarrow \frac{I}{M_1} &= -\frac{\partial H/\partial M_1}{\partial H/\partial I} = -\frac{\alpha \beta (M_2 + \theta' I)(M_1 - \theta' I) - \beta(\beta - 1)(M_2 + \theta' I)^2}{\theta' F(I)} > 0, \\
\Rightarrow \frac{P_1}{M_1} &= -\frac{U_1}{M_1} - (\theta' - 1) \frac{I}{M_1} < 0; \\
\frac{\partial H}{\partial M_2} &= \alpha(\alpha - 1)(M_2 + \theta' I)^{\alpha-2}(M_1 - \theta' I)^{\beta} - \alpha \beta (M_2 + \theta' I)^{\alpha-1}(M_1 - \theta' I)^{\beta-1} < 0, \\
\Rightarrow \frac{I}{M_2} &= -\frac{\partial H/\partial M_2}{\partial H/\partial I} = -\frac{\alpha(\alpha - 1)(M_1 - \theta' I)^2 - \alpha \beta (M_2 + \theta' I)(M_1 - \theta' I)}{\theta' F(I)} < 0, \\
\Rightarrow \frac{P_2}{M_2} &= 1 + \theta' \frac{I}{M_2} = \frac{\beta(\beta - 1)(M_2 + \theta' I)^2 - \alpha \beta (M_2 + \theta' I)(M_1 - \theta' I)}{\theta' F(I)} > 0.
\end{align*}
$$

For case I, the import volume is determined by the following FOC,

$$
\hat{H}(I; M_1, M_2) = \frac{\alpha \beta^\gamma}{(\alpha + \beta)^{\alpha+\beta+1}}(\theta(M_2 + \theta' I) + (M_1 - \theta' I))^{\alpha+\beta+1}(\theta - 1)\theta' - (\theta' - 1).
$$

Under some conditions, $\hat{H}$ is also monotonically decreasing in $I$. It can be discovered that $I$ is linear on $M_1$ and $M_2$ by letting $\hat{H}(I; M_1, M_2) = 0$, i.e.,

$$
I = -\frac{M_1 + \theta M_2}{\theta' (\theta - 1)} + \text{constant},
$$

where the constant is only a function of parameters $\alpha, \beta, \theta$ and $\theta'$. It is then easy to show that:

$$
\frac{I}{M_1} = -\frac{1}{\theta' (\theta - 1)} < 0, \\
\text{and } \frac{I}{M_2} = -\frac{\theta}{\theta' (\theta - 1)} < 0.
$$

The net pollution in the North can be then written as

$$
P_1 = C_1 - C^\alpha E_1^\beta = \frac{\alpha(M_1 - \theta' I) - \beta \theta (M_2 + \theta' I)}{(\alpha + \beta) \theta} - \frac{\alpha \beta^\gamma}{(\alpha + \beta)^{\alpha+\beta+1}}(\theta(M_2 + \theta' I) + (M_1 - \theta' I))^{\alpha+\beta},
$$

where $\theta(M_2 + \theta' I) + (M_1 - \theta' I)$ is a constant by definition. Thus, we have

$$
\frac{P_1}{M_1} = \frac{\alpha - (\alpha + \beta \theta) \theta' \frac{I}{M_1}}{(\alpha + \beta) \theta} > 0.
$$
Similarly, one can obtain that $P_2 = M_2 + \theta'I$, and $\frac{P_2}{M_2} = 1 + \theta' \frac{I}{M_2} = -\frac{1}{\theta'-1} < 0$.

For Case III, we have that $P_1 = 0$, $P_2 = C_2 + I - C^\alpha E^\beta_2 = \frac{\alpha}{\alpha+\beta} (M_1 + M_2) - \frac{\alpha^\beta\beta}{(\alpha+\beta)^{\alpha+\beta}} (M_1 + M_2)^{\alpha+\beta}$. Therefore it is easy to show that

$$\frac{\partial P_1}{\partial M_1} = 0,$$

$$\frac{\partial P_2}{\partial M_2} = \frac{\alpha}{\alpha+\beta} - \frac{\alpha^\beta\beta}{(\alpha+\beta)^{\alpha+\beta-1}} (M_1 + M_2)^{\alpha+\beta-1} > 0.$$

To summarize, the net pollution by the North increases initially, then reaches a peak and then starts to fall, and reaches a bottom and eventually increases, implying an N-shaped EKC from the production account. For the South, net pollution exhibits an inverted U-shaped relationship against relative income.

**Consumption-based EKCs**

In consumption-based accounting, countries’ emissions are associated with their respective consumptions. The embodied emissions from international trade of goods are accounted. Therefore the definition of net pollutions are changed to

$$P_1 = C_1 + I - C^\alpha E^\beta_1,$$

and $P_2 = C_2 - C^\alpha E^\beta_2$.

In case II, notice that for the South, the net pollution is

$$P_2 = M_2 + (\theta' - 1)I$$

from which we obtain

$$\frac{P_2}{M_2} = 1 + (\theta' - 1) \frac{\theta}{\theta' (\theta - 1)} = \frac{\theta - \theta'}{\theta' (\theta - 1)} > 0.$$

For the North, the exercise yields that for net pollution,

$$\frac{P_1}{M_1} = (2 - \theta') \frac{I}{M_1} - \frac{U_1}{M_1}.$$
Then the sign of $\frac{P_1}{M_1}$ can be either negative or positive. For instance, if $\theta' \geq 2$, then $\frac{P_1}{M_1} < 0$ since $\frac{I}{M_1} > 0$, $\frac{U}{M_1} > 0$. For another example, when $\theta'$ approaches to 1, we find that at equilibrium:

$$\frac{P_1}{M_1} = \frac{\alpha}{\alpha + \beta} - \frac{\alpha^\alpha \beta^\beta}{(\alpha + \beta)^{\alpha + \beta - 1}} (M_1 + M_2)^{\alpha + \beta - 1} > 0.$$  

Thus the slope of consumption-based EKC for the rich country in case II is ambiguous. In case I, observe $P_1 = C_1 + I - C_\alpha E_1$, then we have

$$\frac{P_1}{M_1} = \frac{\alpha - (\alpha + \beta \theta) \theta' \frac{I}{M_1}}{(\alpha + \beta) \theta} - \frac{1}{\theta' (\theta - 1)} = \frac{\theta' - 1}{\theta' (\theta - 1)} > 0.$$  

For the South in case II, notice that $P_2 = M_2 + (\theta' - 1) I$, one obtains

$$\frac{P_2}{M_2} = 1 - (\theta' - 1) \frac{\theta}{\theta' (\theta - 1)} = \frac{\theta - \theta'}{\theta' (\theta - 1)} > 0.$$  

For Case III, because $P_1 = M_1/\theta'$, and $P_2 = C_2 - C_\alpha E_2 = \frac{\alpha}{\alpha + \beta} (M_1 + M_2) - M_1/\theta' - \frac{\alpha^\alpha \beta^\beta}{(\alpha + \beta)^{\alpha + \beta}} (M_1 + M_2)^{\alpha + \beta}$, one immediately obtains

$$\frac{\partial P_1}{\partial M_1} = 1/\theta' > 0,$$

$$\frac{\partial P_2}{\partial M_2} = \frac{\alpha}{\alpha + \beta} - \frac{\alpha^\alpha \beta^\beta}{(\alpha + \beta)^{\alpha + \beta - 1}} (M_1 + M_2)^{\alpha + \beta - 1} > 0.$$  

In summary, the consumption-based EKC for the South is monotonically increasing, but for the North can be either monotonically increasing or N-shaped.

### 3 Multi-Regional Input-Output Analysis

National inventories such as those conducted annually by the United Nations Framework Convention on Climate Change account for only those emissions produced within sovereign territories, ignoring the consumption benefit gained by net importing countries through international trade. In recognition of this shortcoming, a number of studies over the past decade have sought to compare production- and consumption-based emissions inventories.
(for a comprehensive, up-to-date review, see Wiedmann T (2009) A review of recent multi-region input-output models used for consumption-based emission and resource accounting. Ecol Econ 69:211–222.). Recent studies have quantified the emissions “embodied” in global trade (i.e., emitted during the production and transport of traded goods and services) among 87 regions in 2001.

Because input-output models are capable in structure analysis, they are used widely in energy and environmental economic analyses.

The current paper uses GTAP database to quantify the carbon emissions from producers’ and consumers’ accounts from a world perspective. We then run simple cross section and panel regressions using the data we calculated from the input-output model.

Firstly, we discuss the pros and cons of the Single Region Input-Output (SRIO) models and Multi-Regional Input-Output (MRIO) models respectively, as well as data constraints. Then, we propose a method parallel to the method proposed by Andrew et al (2009), which effectively overcomes the pitfalls of SIRO and data constraints. We apply this method to obtain figures from producers’ accounts and consumers’ accounts in the years 1997, 2001, and 2004 which correspond to GTAP database versions 5.4, 6, and 7.

3.1 SRIO (based on noncompetitive IO tables)

To analyze based on the noncompetitive IO tables, the horizontal demands in input-output in the baseline model are given in the following equalities.

\[
X = BF_C^d + BF_I^d + BF_E, \quad \text{for domestic products}
\]
\[
M = (A^m BF_C^d + F_C^m) + (A^m BF_I^d + F_I^m) + A^m BF_E. \quad \text{for imports,}
\]

where superscripts \(d\) denotes domestic products, \(m\) denotes imported products; \(X\) is total output column vector, \(M\) is import column vector, \(B\) is the inverse Leontif matrix corresponding to domestic products, \(F^d\) is the final demand vector by domestic consumption for domestic products, \(F_E\) is the export vector, \(F^m\) is the final demand vector by domes-
tic consumption for imported products, $A^m$ is the direct carbon consumption coefficient vector. Subscripts $C$, $I$, and $E$ denote domestic consumption, total capital, and export, respectively.

For CO$_2$ emission problem, if the environmental impacts for unit production and unit import are known (i.e., CO$_2$ emissions for unit domestic production and unit import, $\kappa$ and $\gamma$), then the above model can be written as the following ecological input-output model:

$$
\kappa X = \kappa BF^d_C + \kappa BF^d_I + \kappa BF_E, \quad \text{for domestic products}
$$

$$
\gamma M = \gamma \left( A^m BF^d_C + F^m_C \right) + \gamma \left( A^m BF^d_I + F^m_I \right) + \gamma A^m BF_E, \quad \text{for imports},
$$

where $\kappa BF_E$ is the embodied emission from exports, and $\gamma A^m BF_E$ is the embodied emission from the exports that is attributed to imports$^6$.

In these two equations, $\kappa X$, or the LHS of the first equation, is the total CO$_2$ emission from the production at home, where $\gamma M$, or the LHS of the second equation is the embodied CO$_2$ from imports. This ecological input-output model decomposes and reattributes the total CO$_2$ from production at home, and embodied emission from imports to domestic final consumption and exports. Thus it enables us to measure CO$_2$ emissions for a country from the consumers’ account.

Therefore, the emission by the producers’ account is $\kappa X$ and the emission by the consumers’ account is

$$
\kappa BF^d_C + \kappa BF^d_I + \gamma \left( A^m BF^d_C + F^m_C \right) + \gamma \left( A^m BF^d_I + F^m_I \right).
$$

In general, data on $\kappa$ (unit output CO$_2$ emission) is relatively easy to retrieve, but there can be large variations on $\gamma$ and consequently the final results depending on the methods used to obtain $\gamma$(embodied CO$_2$ emission from imports). Andrew et al (2009) categorize the existing studies into 3 categories per approaches in processing and estimating the embodied CO$_2$ from imports. They are: Domestic Technology Assumption (DTA); Unidirectional Trade, and Multidirectional Trade. The accuracy of the methods are compared and evaluated.

$^6$That is the embodied emission used for re-export with or without processing.
If one calculates the consumption based CO₂ emission from a single country model, it considers unidirectional imports and exports, therefore the incidence of the exports from imports \(\gamma A^m B F_E\) is undetermined. Thus, from a global perspective, CO₂ emission is underestimated. Because of this, one can hardly apply SRIO to analyze global emission problems.

### 3.2 MRIO

A full MRIO model links all countries and regions in the world by a global trading matrix, and distinguishes the imports for intermediates and final goods for all commodities for each country. Let \(X_s\) be country \(s\)’ output vector (whose elements are \(X_{si}\) where \(i\) is the industry index), \(Z_{rs}\) be the goods of country \(r\) used for production at country \(s\) (where the elements are \(Z_{rsij}\) which refers to the quantity of product \(i\) in industry \(j\)), \(Y_{rs}\) be country \(s\)’ domestic final demand on country \(r\)’s products (whose elements are \(Y_{rsi}\) which is the domestic final demand for product \(i\)). Then first we obtain the input coefficient vectors \(A_{rs}\) by output vectors \(X_s\) and input matrices \(Z_{rs}\), i.e., the quantity of products of country \(r\) used by per unit production of country \(s\) (whose elements are \(A_{rsij}\) or the quantity of product \(i\) used...
by industry $j$). Thus, the full MRIO model can be written as:

\[
\begin{pmatrix}
X_1 \\
X_2 \\
X_3 \\
\vdots \\
X_m
\end{pmatrix}
= \begin{pmatrix}
A_{11} & A_{12} & A_{13} & \cdots & A_{1m} \\
A_{21} & A_{22} & A_{23} & \cdots & A_{2m} \\
A_{31} & A_{32} & A_{33} & \cdots & A_{3m} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
A_{m1} & A_{m2} & A_{m3} & \cdots & A_{mm}
\end{pmatrix}
\begin{pmatrix}
X_1 \\
X_2 \\
X_3 \\
\vdots \\
X_m
\end{pmatrix}
+ \begin{pmatrix}
\sum_y y_{1r} \\
\sum_y y_{2r} \\
\sum_y y_{3r} \\
\vdots \\
\sum_y y_{mr}
\end{pmatrix}
\]

By solving the inverse matrix one obtains the final demand induced output that is similar to SRIO. The MRIO is completed by multiplying the unit ecological impact factors by outputs of the countries. The emissions that linked to a country’s final demand is the consumption-based emission.

In the full MRIO model, because the foreign imports for intermediate inputs and final demand in all countries are separately recorded, the problem of attribution indeterminancy on re-export in the SRIO is avoided, and consequently the under-estimation is also avoided.

However, in realistic situation, intermediate inputs from imports and final consumption goods imports ($Z_{rsij}$ and $Y_{rsi}$) are not separately treated in data, thus creating difficulties in applying MRIO directly. Currently, even GTAP data does not provide separate intermediate input imports and final consumption goods imports at country level, despite the detailed trade matrices.

Researchers use either DTA simplification (Battjes et al., 1998, Lenzen et al. 2004) or unidirectional trade MRIO models (Lenzen et al., 2004) to process.

Andrew et al (2009) use the trade matrices in GTAP data ($e_{rsi}$) and divide proportionally to estimate $Z_{rsij}$ and $Y_{rsi}$ (see also in Peters and Hertwich, 2008) who calculated the consumption-based CO$_2$ emissions in a MRIO model. The core assumption in the calculation is that the structure of imported goods are used as a substitute to the foreign intermediate input content (as a technological structure) in all industries, as well as the implied preference for imports from all other countries in the domestic final goods demand for the country of interest. Obviously, however, these structures ought to be different.

Most of the recent studies on carbon footprint use MRIO model and GTAP database. For instance, Peters and Hertwich (2008) calculated the emission in trade for 87 countries
and regions in 2001 and found that the embodied emission in trade accounts for more than a quarter of world’s total emission. In particular, for China, the embodied emission in export amounts to 24% of the total emission within China and embodied emission from imports is only 7%. Wilting et al (2009) use v6 of GTAP to study GHG emissions from both consumers’ and producers’ perspective. Andrew et al (2009) survey the existing methods in calculating carbon footprint using input-output tables, and discuss the impact of trading partners on the accuracy of the results.

3.3 Using SRIO to approximate MRIO: Our Approach

We evaluate the approach taken by Andrew et al (2009) and propose another approach which is equivalently effective to the full MRIO. Thus, we provide an alternative choice for MRIO calculation. The essence of the approach is to approximate by infinite loop calculation on the SRIO.

The approach is constituted by three main equations, where the first is calculated once for the domestic produced products, and the latter two approximate in infinite loops.

(1). For domestic outputs, applied to 113 countries and regions:

\[ \kappa X = \kappa BF^d_C + \kappa BF^d_I + \kappa BF_E, \]

(2). the relationship between export emission coefficients \( \varepsilon_{s,i} \) and import emission coefficients \( \gamma_{r,i} \)

\[ \gamma_{r,i} = \sum_s \varepsilon_{s,i} E_{sr,i} \frac{E_{sr,i}}{M_{r,i}}, \]

where \( \gamma_{r,i} \) is embodied emission in country \( r \)'s unit import product, \( \varepsilon_{s,i} \) is the calculated embodied emission in country \( s \)' export of goods \( i \) measured by FOB prices, \( M_{r,i} \) is country \( r \)'s import value of good \( i \), \( E_{sr,i} \) is the trade matrix measured by FOB prices.

(3). Imports, applied to all 113 countries and regions:

\[ \gamma M = \gamma (A^m BF^d_C + F^m_C) + \gamma (A^m BF^d_I + F^m_I) + \gamma A^m BF_E. \]

In the first round calculation, the incidence of embodied emission in countries’ imports used for exports are not determined. The calculations are repeated for infinite times in a
loop to decompose it into all other countries' final demand until it reaches zero. In each round, \( \varepsilon_{s,i} \) and \( \gamma_{r,i} \) are recalculated. In practical situations, if \( \gamma A^m B F_E \) is one third or one fourth in proportion in the first round, it takes about 40 rounds to approximate zero (8.2E-20).

The approach assumes that the weight of foreign intermediate input content in an industry in any country is the same with the weight of imports in final consumption goods.

4 Econometric Analysis

In this section, we first review the problems in existing empirical researches on EKC, and estimate the shapes of producer-based EKCs using panel data available from World Bank, then run econometric regressions on the results obtained from our input-output calculations and compare them to the results in pure econometric studies.

Several early authors used ordinary least squares (OLS) estimation with cross section data in their empirical studies on EKC. Seldon and Song (1994) found that an inverted U-shape exists between CO2 emissions and income. However, Shafik (1992) suggested a monotonically increasing concern between CO2 and per capital income. This approach makes the basic assumption that the environment-income relationship is internationally homogenous (Panayotou, 1993 and Shafik, 1994).

Thus, a second wave of papers used panel data sets to include country-specific effects and other underlying structural determinants into the estimation, which allows some heterogeneity across sectional units (e.g., Cole and Elliott 2003, Cole 2004, Roca et al. 2001, Heerink et al. 2001, Barrett and Graddy 2000, Gale and Mendez 1998, Kaufman et al. 1998, Torras and Boyce 1998 and Panayotou, 1997). Grossman and Krueger (1995) detected the N-shaped curve between SO\(_2\) emissions and economic growth. None the less, using the same database extended by 10 years, Harbaugh et al. (2000, 2002) found a rotated-S function instead of the N curve.

The most widely used single-equation approach to the EKC is to estimate a polynomial relationship (up to degree three) between emissions (as the dependent variable) and GDP on
cross-section, time series or panel data. This approach dates back at least to the seminal work of Grossman and Krueger (1991, 1993, 1995) who find evidence for an inverse U-shaped relationship between per capita GDP and GHG. Survey papers like Stern (2004) report more than 100 articles published on refereed journals are of this type. The standard parametric EKC regression model is written as

\[
\ln (e_{it}) = \alpha_i + \theta_t + \beta_1 \ln (y_{it}) + \beta_2 (\ln (y_{it}))^2 + u_{it}, \tag{27}
\]

where \(e_{it}\) and \(y_{it}\) are per capita emissions and GDP in country \(i\) and period \(t\) respectively; and \(u_{it}\) is a noise term.

The shape of the functional relation is determined by \(\beta_1\) and \(\beta_2\), which does not depend on country specific parameter. This induces the homogeneity problem which is central to the panel analysis of the EKC, i.e., all regions exhibit the same GDP-emissions pattern. In particular, they all have the same turning point at \(y^* = \exp \left( -\frac{\beta_1}{2\beta_2} \right) \) though the peak emission levels may differ across countries. This is illustrated in the figure below.

The only way to completely avoid heterogeneity issue is to use single country time series data. Some studies indicate that the appearance of a delinking between pollution and income should be attributed to country-specific characteristics such as technological progress, structural evolution, etc. The introduction of consumption-based accounting
complicates the problem further.

Another drawback of the quadratic function is that it is symmetric, that is, the uphill portion of the curve has the same slope as the downhill part. This implies that, when income goes beyond some threshold level, environmental degradation will decrease at the same rate as it previously increased, which is also very unlikely, as many forms of environmental degradation can be extremely difficult to undo. For instance, most pollutants tend to accumulate and persist for a long time, so that they are generally much harder to mitigate than to produce.

More specifically, as Cole et al. (2001) points out, a cubic function implies that environmental degradation will eventually tend to plus (or minus) infinity as income grows over time. Similarly, a quadratic concave function implies that environmental degradation could eventually tend to zero (or even become negative) at sufficiently high income levels, which is not supported by empirical evidences.

To illustrate the difference in results by different data sources and econometric treatment, we run simple econometric regressions first. The benchmark data is collected from the World Development Indicators (WDI) of World Bank, including CO$_2$ emission per capita, GDP per capita, and share of industry on GDP.

The fixed effect panel data regression indicates that EKC is N-shaped rather than inverted U-shaped, which differs from the empirical result of Grossman and Krueger (1991). The estimated coefficient of industry bears the expected positive sign and is statistically significant at 1% significance level, suggesting that 1% decrease in the share of industry production in GDP will decrease the CO$_2$ emissions by 0.051 metric tons per capita. The time trend, the proxy for technology growth, is statistically significant at 10% level and has a very small but statistically significant positive impact on emissions. The following figure illustrates the panel regression results. The two turning points are $26,420 and $51,680 at 2000 constant US dollars.

To avoid the heterogeneity issue mentioned earlier, we run separate regressions on time series data for the 110 countries and regions. When dealing with the time series data, the problems of high degree multicollinearity between time trend and GDP is found in some
countries and time trend is removed for the significance of the regressions. The time series regressions tell us that for some countries such as China, the EKC is N-shaped (depicted in figure below). However since $\beta_1$ is always positive, there is essentially no turning point.

We then estimate the EKCs for individual countries or regions separately and found several shapes: the inverted U, rotated S (including N), U, and linear. These are plotted below.

de Bruyn and Opschoor (1997) and Sengupta (1997) identify that CO$_2$ exhibits an N shape EKC, meaning that the environmental degradation starts increasing again after a
decrease to a certain level.

The following figures depict econometric results for MRIO results. Figure xx., xx., and xx. depict the EKCs from 1997, 2001 and 2004 MRIO results. Each of them is estimated in production-based and consumption-based emissions in a cross-sectional fashion. It is found that in 1997 and 2001, the consumption-based EKC are all linear, implying no turning points, despite the invertedly U-shaped EKCs from the producer’s account. The consumption-based EKC for 2004 is invertedly U-shaped, however it is much flatter than
the production-based one, with a turning point out of sample at a per capita income of US$799,338, a figure far beyond the richest country’s current per capita income.

The MRIO results for 2004 yields an slightly inverted U-shaped consumption-based EKC. However, even though the fitted consumption-based EKC is inverted U-shaped, the peak is out of sample at a per capita income of US$799,338.

The single equation regression for pooled data from MRIO results for all three years, namely 1997, 2001, and 2004, is estimated. The results imply that the consumption-based EKC, although invertedly U-shaped, has a turning point far beyond the highest per capita income in the world.

Finally, a panel data regression is carried out for the MRIO results. The panel has a very short time dimension, i.e., only 3 observations for each time series. The results are then not so reliable. Indeed, the panel regression shows a downward sloping linear relationship, which is either contradictory to real world observations or common sense.

5 Conclusion

Despite the well perceived leakage problem and growing literature on empirical quantification of the embodied carbon leakage in international trade, few attempts are made to build
1997 EKC

\[ y_{\text{Consumer}} = 0.6248x + 3.9453 \]
\[ y_{\text{Producer}} = -0.1689x^2 + 3.5357x - 9.1776 \]

2001 EKC

\[ y_{\text{Consumer}} = 0.7965x + 1.6436 \]
\[ y_{\text{Producer}} = -0.1505x^2 + 3.2539x - 8.2512 \]
2004 EKC

Consumer: \( y = -0.0719x^2 + 1.9581x - 2.9608 \)
\( p = 0.0199^{***} \)  \( p = 0.327^{***} \)  \( p = 1.300^{**} \)

Producer: \( y = -0.1103x^2 + 2.5754x - 5.5454 \)
\( p = 0.0215^{***} \)  \( p = 0.352^{***} \)  \( p = 1.403^{***} \)

Consumption based EKC for pooled data
\( y = -0.08x^2 + 2.0538x - 2.8889 \)

\( p = 0.0215^{***} \)  \( p = 0.352^{***} \)  \( p = 1.403^{***} \)
Pooled EKC

Consumer: $y = -0.08x^2 + 2.0538x - 7.2309$

(0.021)***   (0.338)***   (1.343)**

Producer: $y = -0.1361x^2 + 3.0086x - 7.2309$

(0.015)***   (0.251)***   (0.997)***

Panel data EKC

Consumer: $y = -0.343x + 11.375$

(0.130)***   (1.712)***

Producer: $y = -0.205x + 9.840$

(0.052)***   (0.436)***
a theory model. However when the pollutant is GHG which is globally transboundary, the effects and consequences of relocating firms or import goods overseas are not straightforward. Questions related to these are generally not easy to answer. For instance, if pollution is transboundary, why would a country displace production off the border? The embodied emission is partially understood from a theoretical perspective. The current paper fills the gap.

In this paper, we consider a two-country North-South open economy model à la Andreoni and Levinson (2001) in which production is accompanied with emission of a global pollutant. Assume that the North has a clean but expensive production technology relative to the South. There are several effects when trade takes place, i.e., wealth effect in public good provision (Boxed Pigs game), pro-consumption effect in the South due to gains from trade, and production cost-saving in the North because of imports. The first effect says that the gains from trade makes the North “richer” hence it will provide more pollution abatement. The second effect indicates that the South will consume more (and produce more) and therefore emit more compared to no trade scenario. The third effect refers to the fact that the North saves direct production costs by importation. The savings is then divided to abatement spendings and additional consumptions in a Nash fashion. It is then plausible that North’s Environmental Kuznets Curve (EKC) is inverted U-shaped from producer’s account but both regions’ EKC are monotonically increasing from consumer’s account. This is the so-called leakage effect where production in developed country is displaced to the developing country.

In the second part of the paper, we compute the final good consumption-based CO$_2$ emissions using a fully coupled multiregional input–output (MRIO) model constructed from 2004 global economic data disaggregated into 113 countries/regions and 57 industry sectors. The result shows that the consumption-based EKC (logarithm of per capita emission against logarithm of per capita income) for CO$_2$ is either linear or a much flatter inverted U-shaped with a peak far out of the sample.
References


6 Appendix

6.1 Off-equilibrium cases.

Case III. $0 < \lambda_2 < \lambda_1$.

In this case, (7) and (8) hold in strict inequalities, and according to the complementary slack conditions, $C_1 = E_1 = 0$. Note since the utility functions are strictly increasing in total abatement efforts, total abatement can not be 0, hence $E_2 \neq 0$.

Then the first subcase here is $C_2 = 0 < E_2$ and the complementary slack conditions are $\lambda_2 = \beta C^\alpha E^{\beta-1} > \alpha C^{\alpha-1} E^\beta$. From the resource constraints, we know that $E_2 = M_2 + (\theta - 1) I$, hence the world total consumption and abatement are respectively $C = I$, and $E = M_2 + (\theta - 1) I$. However this case does not arise in equilibrium. It can be proven by contradiction. Suppose it arises in equilibrium, then the allocation of the resources must be $I = C = M_1/\theta'$, and $E = M_2 + \frac{\theta - 1}{\theta'} M_1$, where the corresponding utility levels for the rich and poor countries are respectively

$$U_1 = \left( \frac{M_1}{\theta'} \right)^\alpha \left( M_2 + \frac{\theta - 1}{\theta'} M_1 \right)^\beta$$

and

$$U_2 = \left( \frac{M_1}{\theta'} \right)^\alpha \left( M_2 + \frac{\theta - 1}{\theta'} M_1 \right)^\beta - \frac{M_1}{\theta'}.$$

Then it can be shown that $\lambda_1 = \frac{\partial U_1}{\partial M_1} < \lambda_2 = \frac{\partial U_2}{\partial M_2}$. In particular,

$$\lambda_1 - \lambda_2 = \frac{1}{\theta'} \left( \alpha \left( \frac{M_1}{\theta'} \right)^{\alpha-1} \left( M_2 + \frac{\theta - 1}{\theta'} M_1 \right)^\beta - \beta \left( \frac{M_1}{\theta'} \right)^\alpha \left( M_2 + \frac{\theta - 1}{\theta'} M_1 \right)^{\beta-1} \right) < 0$$

and it contradicts the complementary slack condition $\lambda_2 = \beta C^\alpha E^{\beta-1} > \alpha C^{\alpha-1} E^\beta$.

Case IV. $0 < \lambda_2 = \lambda_1$.

In this case, (7) holds in strict inequality. By the complementary slack condition, $C_1 = 0$. If $E_1$, $E_2$, $C_2 > 0$, then according to the complementary slack condition, $\lambda_1 = \lambda_2 = \vdots$
\[ \beta C^\alpha E^{\beta-1} = \alpha C^{\alpha-1} E^\beta. \] By the resource constraints, we have:

\[
E_1 = M_1 - \theta' I \\
C_2 = \frac{\alpha}{\alpha + \beta} (M_2 + M_1) - I \\
E_2 = \frac{\beta}{\alpha + \beta} (M_2 + M_1) + \theta' I - M_1.
\]

World’s total consumption and abatement are

\[ C = \frac{\alpha}{\alpha + \beta} (M_2 + M_1), \quad \text{and} \quad E = \frac{\beta}{\alpha + \beta} (M_2 + M_1) \]

respectively. Note that \( C \) and \( E \) are independent of the trade volume. The utility of the North can be written as

\[
U_1 = C^\alpha E^\beta - C_2 = \frac{\alpha \beta}{(\alpha + \beta)^{\alpha+\beta}} (M_2 + M_1)^{\alpha+\beta} - \left( \frac{\alpha}{\alpha + \beta} (M_2 + M_1) - I \right).
\]

It is obvious that \( U_1 \) is strictly increasing in \( I \), thus \( I = M_1 / \theta' \) which is in contradiction with \( E_1 > 0 \). Contradictions arise if we assume \( E_1, E_2, C_2 > 0 \). Therefore case II does not arise in equilibrium.

**Case V.** \( 0 < \theta \lambda_1 < \lambda_2 \)

In this case, (4) and (5) hold with strict inequalities, hence \( C_2 = E_2 = 0 \) which is in contradiction with \( \lambda_2 > 0 \).

Hence cases III, IV and V do not arise in equilibrium.
### 6.2 MRIO Results

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