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Trading Away Damage: Quantifying Environmental Leakage through Consumption-based, Life-cycle Analysis

Abstract

This research quantifies the extent to which the US has shifted the environmental impact associated with the goods it consumes to other countries through trade. To achieve this, we use a life-cycle, consumption-based approach to measure the environmental impacts embodied in US trade activities for global warming potential (GWP), energy, toxics, and the criteria air pollutants. We use these values to determine the amount of environmental impact “leaked” from current, production-based approaches to analyzing national environmental trends for the years 1998-2004. We find that with reasonable assumptions about the environmental intensity of imports and exports, this leakage exceeds 10% for all studied impacts, exceeds 25% for GWP, energy, and most criteria air pollutants, and exceeds 80% for lead emissions and toxics. By including the environmental impacts embodied in trade activities into national environmental accounts, we provide consumption-based, US per capita, environmental impacts, which we use to evaluate the relationship between income and environmental impact. We find evidence for rising per capita environmental impacts with rising income in the US, contra the Environmental Kuznets Curve. The paper concludes with a discussion of the implications for international environmental policy of increasing embodied emissions in trade.

Keywords: input-output analysis, life cycle assessment, environmental leakage, environmental terms of trade, industrial outsourcing, climate policy

I. Introduction

The relationship between environmental quality and trade has become a topic of widespread interest since the early 1990s. The ability of wealthy countries to export environmental damage via direct trade in pollution (e.g. hazardous waste) is one well-understood

process of environmental deintensification. Research has focused less on the environmental impacts embodied in traded goods or on how environmental damage is externalized through the outsourcing of environmentally intensive production processes. Because wealthy countries are increasingly importing goods with embodied environmental impact instead of producing them domestically (Streets et al. 2006), they are able to unlink production and consumption. This has been little studied in environmental trends analysis to date, but has important implications for the success of future international environmental treaties and conventions. This research quantifies the extent to which the US has shifted the environmental impact associated with the goods it consumes to other countries through trade.

The starting point for this study is the recognition of a shortcoming in the ways in which the economy and the environment are measured in national environmental trends analysis. Current approaches are typically based on a comparison between national environmental accounts and gross domestic product (GDP). This method has been called a “production-based approach” because it uses national environmental accounts to quantify the environmental impact of production activities without differentiating between goods produced for domestic versus international consumption. These accounts are then compared to GDP to calculate environmental intensity, which is reported as gross environmental impact of a given type per unit of generated GDP. But national environmental accounts show an incomplete picture of the emissions that can be attributed to the US economy. A significant quantity of goods are produced outside of US borders, and then imported to satisfy US demand, or produced in the US and sent abroad to satisfy the demand of our trading partners. However, current environmental indicators do not account for environmental impacts embodied in traded goods. This paper sets out to consider the

limitations of such a production-based approach to environmental indicators for the analysis of US environmental trends.

To measure the full environmental impacts associated with US expenditure requires a consumption-based approach with particular attention to international trade (Rothman 1998). This research adopts such an approach using economic input-output life cycle assessment (EIO-LCA) for four categories of environmental impact: global warming potential, energy use, toxic release, and the criteria air pollutants (carbon monoxide, particulate matter < 10 μ m, sulphur dioxide, nitrogen oxides, lead, and volatile organic compounds). While recent studies have attempted to advance consumption-based approaches to environmental indicators, they are either based on a small subset of economic sectors (Wyckoff and Roop 1994, Janicke et al. 1997, Cole 2004a), lack comprehensive data for the economy under study (Rothman 1998), or examine only one environmental impact (Suri and Chapman 1998, Antweiler et al. 2001, Ferng 2003). The few studies that have analyzed trade and environment relations at an aggregate level for the entire US economy have not used a life-cycle approach (Antweiler 1996, Atkinson and Hamilton 1996, Muradian et al. 2002, Cole 2004b), which the present study provides.

The coupling of EIO-LCA with US trade data provides a novel approach to analyzing the aggregate US balance of environmental impacts embodied in traded goods and services. While most studies of the relationship between trade and environmental impact, especially those examining the Environmental Kuznets Curve (EKC) hypothesis, are modeled econometric studies based on cross-country, time-series data (see Grossman and Krueger 1992, Seldon and Song 1994, Shafik 1994, Cole et al. 1997, Spangenberg 2001), this study takes a different approach. EIO-LCA advances current understandings of trade and the environment not by exploring new relationships between regulation and the environment or by including new

dependent variables, but rather by providing a more comprehensive approach to using existing data for the study of environmental trends.

The goal of this work is twofold. First, it quantifies the difference between environmental impacts under a consumption-based and a production-based approach to national environmental accounting for the US economy from 1998 to 2004. This difference is the quantity of environmental impact not accounted for in production-based approaches and represents the net environmental impact embodied in traded goods and services, which has been described as the balance of embodied emissions in trade (BEET) (Muradian et al. 2002). In other words, BEET is the environmental impact that has “leaked” from current production-based methods of assessing environmental impact. This study quantifies the leakage from US environmental accounts for the four abovementioned environmental impacts. Second, this research compares national environmental intensities under production- versus consumption-based approaches to environmental accounting. It leverages these numbers into an evaluation of the empirical veracity of the EKC for the US economy.

This paper is organized as follows. Section II discusses the relationship between trade and the environment, largely through a review of EKC studies, and how an EIO-LCA, consumption-based approach provides a useful way to evaluate this relationship. Section III describes this study’s basic methodology. In section IV, we describe the calculation of BEET along with the paper’s primary results. These include the US BEET, leakage percentages, and aggregate, consumption-based US environmental intensities for each environmental impact. Section V disaggregates three different effects that contribute to leakage from the production-based national environmental accounts. Section VI uses the results from a parametric analysis to consider variations in aggregate US environmental intensity given differences in the relative

intensity of imports and exports. Section VII concludes by exploring the implications of the results from Sections IV and VI for environmental policy and regulation.

II. Trade, Environment and EKC

In the early 1990s several authors hypothesized an Environmental Kuznets Curve¹ (EKC) to describe the relationship between environmental quality and economic growth (see Grossman and Krueger, 1992 and Shafik, 1994). The EKC is an inverted “U-shaped” curve displaying a historical relationship, usually based on empirical studies of urban emission levels in the US or Europe (see Seldon and Song 1994, Grossman and Krueger 1995, Harbaugh et al. 2002), whereby emissions increase with national income before reaching a turning point at which emissions decrease as economic growth continues. The Y-axis in longitudinal EKC studies was originally in units of concentration or per capita emissions, and the X-axis in GDP or time units.

The EKC has always been controversial, resulting in quantitative analysis in the North² to determine its validity across different environmental indicators (Grossman and Krueger 1995, Cole et al. 1997). It is generally found that the EKC accurately represents historical trends for these countries for certain indicators (urban air pollutants, sanitation, access to clean water) and not others (municipal waste, carbon dioxide emissions, direct material flows) (Shafik 1994, Seppälä et al. 2001).³ The EKC is putatively explained by economic theory, which states that the ratio of marginal utility of a unit of environmental quality to the marginal utility of a unit of income is low in early stages of development, but increases as countries become wealthier

¹ The EKC is named after the better-known Kuznets Curve, which describes a similar relationship between income inequality and economic growth (Kuznets 1955).

² “North” and “South” refer to industrialized and industrializing countries, respectively.

³ Harbaugh et al. (2002) find, however, that the EKC does not hold for urban air pollutants upon “merely cleaning up the data, or including newly available observations.”

(Hettige et al. 1997). A policy implication commonly extracted from this observation is that growth will lead to an improved environment and growth, thus, should be promoted in the interest of the environment (Beckermann 1992).

Numerous studies have been conducted since 1995 debunking the EKC (see Arrow et al. 1995, Farber 1995, Grossman and Krueger 1995, Lash 1995, Daily et al. 1996, Karr and Thomas 1996, Schindler 1996). Despite most criticisms, “the current debate is less on the validity of [the EKC] than on its interpretation” (Sprangenberg, 2001: 176). Thus, the general “inverted-U” relationship remains at least a frame of reference for time-series, if not cross-sectional, data against which the paths of environment and development relations for many countries are compared (see Lopez and Mitra 2000).

Most studies of the EKC share the limitation described in this paper’s introduction: they look only at production within a country’s borders and ignore international production to satisfy domestic demand. This means that the EKC is often explained in terms of improved production efficiency (see Grossman, 1995, Panayotou, 1993) without discerning the relative contribution to decreased pollution levels due to technological change versus the outsourcing of environmental impact via trade (Rothman, 1998).

Evidence increasingly suggests that, indeed, structural changes in the sectoral composition of domestic production and trade (without concomitant changes toward less environmentally intensive consumption) are driving reductions in production-based environmental intensities in industrialized countries (Suri and Chapman 1998, Fischer-Kowalski and Amann 2001, Cole 2004b, Rhee and Chung 2006). This is explained by two different dimensions of what is typically referred to as industrial outsourcing: an increasing percentage of intermediate inputs being imported rather than domestically produced (Jacobsen 2000), which

reduces the material and energy demand of domestic production, and the shifting of the production of environmentally intensive consumer goods outside of US borders (Suri and Chapman 1998). Production-based analyses of environmental trends treat industrial outsourcing in the North as a net reduction in environmental impact from national accounts. The flip side of industrial outsourcing is the increase in the environmental burden in the South for goods produced to meet Northern demand.⁴ This increase in environmental impact has been called displaced environmental load, or leakage.

This work sets out to quantify the US economy's displaced environmental load, measured by BEET, and to continue the evaluation of the EKC as an observable environmental phenomenon. Rather than testing the applicability of the "inverted U-shape" to the South, we return to the question of the validity of such a curve in representing US environmental trends. The EKC predicts a gradual departure from environmental concerns in wealthy countries. As countries get wealthier, the curve asymptotes to low pollution levels, suggesting that those countries are permanently clean. This study explores what can be called "late curve analytics." That is, how new patterns in trade and industrial outsourcing in the North, which is presented at the tail end of the EKC for most pollutants, may result in environmental impacts that look different than the EKC suggests. In particular, there might be an upward sloping tail at the bottom of the downward sloping segment of the EKC that has not yet been sufficiently examined or theorized. We thus hypothesize that the environmental intensities of wealthy countries could increase with wealth and/or time, contra the EKC. This study pursues such a project by improving on previous macro studies of environmental trends in three ways, described in turn in the next three sub-sections.

⁴ For example, Streets et al. (2006), using a regional atmospheric air transport model, show that 5-30% of ambient air pollutant concentrations in the Pearl River Delta of China are caused by the production of goods for export.

2.1 Consumption-based approach

The distinction between production- and consumption-based approaches does not lie in the location of environmental impact within a product's life-cycle (production phase versus use phase or end-of-life), but rather in the question of to whom the environmental damage is attributed. The "consumption-based" approach is a framework for attributing the environmental impacts of *production activities* on the basis of who *consumes* the product. This limited definition of "consumption-based" is used because environmental impacts associated with consumption activities—the use and post-use stages of a product's life-cycle—are already attributed to the country in which consumption takes place in current environmental accounts.⁵ The macro, consumption-based approach used here accounts for the environmental impacts embodied in the production of goods for consumption. It focuses on the distribution of environmental impacts across countries based on the location of the consumer and assumes that consumers bear the full responsibility for the impacts of producing the goods they consume.

To quantify the total environmental impacts of US consumptive activities, we must measure the international allocation of environmental impacts. By including pollution that is attributable to products used to satiate US consumer demand into environmental accounting, we more accurately represent US environmental impacts on a global scale (Muradian et al. 2002). Existing consumption-based approaches to environmental trends analysis that make use of environmental intensity use GDP as the metric for the economy, even though it is a production-based measure (see Rothman 1998). This approach uses GDP as a proxy for purchasing power or

⁵ For recent uses of LCA to examine the micro dimensions of consumption, see the reviews by Hertwich (2005) and Tukker and Jansen (2006).

consumptive expenditure, a simplification which we also follow. According to this convention, purchasing power determines the environmental impact of a country's economy.⁶

2.2 Including trade

Most studies of environment and trade have a thin conception of the relationship between the two. They either (a) focus solely on how open trade changes environmental regulations or production processes in a country, without emphasis on trade in environmental impact (Vogel 1995, Antweiler et al. 2001), or (b) consider trade in environmental impact only to the extent that actual resources or pollutants are themselves traded (e.g. hazardous materials) (O'Neill 2000). Few studies account for environmental impact embodied in trade, which is the present study's second improvement over the production-based approach.

Most EKC studies, in particular, do not adequately address the issue of trade (Rothman 1998). These studies use an international normative framework; that is, the EKC is used to make statements about the course that international economic development should take. However, the explanatory framework for environmental impact has system boundaries confined to the national scale. Thus, the policy recommendation stemming from the EKC is to promote growth, often through open trade. However, the framework provided for explaining the condition of the environment fails to consider the possibility that domestic environmental impact is associated with international trade.

In order to maintain credibility in analyses of contemporary environmental trends in the context of economies with high levels of trade, these normative and explanatory frameworks must be reconciled. Doing so requires explicit accounting of the environmental impacts

⁶ Using the same denominator (GDP) when calculating both consumption- and production-based environmental intensities also allows for a more direct comparison of these intensities. In particular, the scale effect (extra pollution abroad due to the US trade deficit) is only apparent when both intensities use the same denominator.

embodied in international trade, because only then can environmental analysis account for the geographical delinking of production and consumption activities. However, not all consumption-based approaches explicitly include international economic flows (see Gawande et al. 2001). The present study does so by quantifying the pollution embodied in goods imported to the US. This allows us to evaluate the extent of leakage from national environmental accounts.

2.3 EIO-LCA

Environmental impacts embodied in trade have been included in a select few analyses of US environmental trends (see Antweiler 1996, Atkinson and Hamilton 1996, Muradian et al. 2002, Cole 2004b). These studies use the composition of trade to determine the distribution of pollution and resource use between countries. However, the depth of impacts included in these studies only includes those that arise from the final stage of production of the good or service, not the good or service's full production life-cycle, which includes the environmental impacts of all intermediate inputs as well as the inputs into those intermediate inputs.

Quantifying the full impact of a good or service requires rigorous empirical data collection. Such data do not exist on the scale of the global economy. To address this data deficiency, many have turned to aggregate measures of environmental impact, including the "ecological footprint" (Wackernagel and Rees 1996), material flows analysis (Seppälä et al. 2001), and environmental space (Spangenberg 2001). Alternatively, input-output analysis has been implemented to examine energy and pollution embodied in international trade (see Wyckoff and Roop 1994, Battjes et al. 1998, Kondo et al. 1998, Lenzen 1998, Jacobsen 2000, Machado et al. 2001, Munksgaard and Pedersen 2001, Ferng 2003, Mongelli et al. 2006). Such analyses make important contributions to the study of embodied environmental impact. But, while some

of these studies do account for the life-cycle impact of production activities, they focus only on carbon dioxide emissions and energy use and/or are aggregated to a small set of economic sectors. This approach, furthermore, has yet to be applied to EKC analysis and has been applied only to a limited extent in examining the US economy. We build on these studies, with particular attention to the EKC hypothesis and the US economy. We do so through LCA of sixty-five aggregated sectors of the US economy.

LCA has increasingly been recognized as the most robust method for accounting for the resource flows associated with products and services (Graedel 1998, UNEP 2004). Process-based LCA has been the most widely used method of LCA to date. Traditionally based on analyzing the environmental impacts of a particular process or production stage (e.g. a manufacturing unit), this approach draws arbitrary system boundaries that often extend only to direct suppliers and not the full supply chain inputs (Curran 1993). This leads to direct input analysis, a simplification of the full life-cycle of production (Hendrickson et al. 1998).

An Economic Input-Output LCA (EIO-LCA) model has recently been developed that uses a system boundary that includes the entire US economy, thus avoiding the simplified treatment of the supply chain required in process-based LCA (Hendrickson et al. 1998, Hendrickson et al. 2006). This model uses an input-output model of the entire economy to identify all economic activity required directly or indirectly to produce a set of commodities. Then, a table of environmental intensities for each type of production activity is used to calculate the complete life-cycle impact of the final commodities. This model can be distilled down to a list of life-cycle environmental intensities for each commodity produced by the economy, for each of the environmental impacts examined in this study. Our general approach in the present study is to apply these sectoral environmental intensities, which are described more fully in the

next section, to sector-wise data on US imports and exports. This yields the total life-cycle environmental impact embodied in US imports and exports, as well as the balance of embodied emissions in trade (BEET). We repeat this calculation for seven different years (1998-2004) and examine how BEET changes with time. This procedure and the results for BEET are shown in Section IV, but first, in Section III we describe the details of the EIO-LCA model and how we use it to assess macroeconomic emission trends.

III. Method

In EIO-LCA, the supply chain is modeled using a general equilibrium economic input-output (EIO) model (Leontief 1986). Industries or commodities making up the economy are divided into a number of separate sectors. Then a “direct requirements” matrix is built for the whole economy, showing the inputs that any sector of the economy requires from all other sectors to produce a unit of output. The EIO modeling approach operates on the assumption that increasing the output from any sector requires a proportional increase in each input received by that sector from all other sectors. Following this assumption, the direct requirements matrix is transformed algebraically into a “total requirements” matrix, which shows the total amount of both direct and indirect inputs that are required from all sectors of the economy to produce a dollar of final output from a given sector (Hendrickson et al. 1998, Guo et al. 2002). This matrix can then be used to estimate the gross output induced in every sector of the economy to supply any set of final outputs. The EIO-LCA model then uses a table of environmental intensities for each industrial sector to calculate the total environmental impact associated with the specified set of final outputs.

We have adapted the EIO-LCA method described by Hendrickson et al. (1998, 2006) to analyze the life-cycle environmental impacts of U.S. trade over a multi-year period. Our model's basic equation for each type of environmental impact in each year, due to the production of a given set of final outputs, is given by:

$$e = \mathbf{iRDTf} \quad (1)$$

Here, e shows the total environmental impact created when the economy meets the final demands \mathbf{f} . \mathbf{T} is the total requirements matrix; \mathbf{D} is a diagonal matrix of price deflators; \mathbf{R} shows the environmental impact per dollar of gross output from each industrial sector; and \mathbf{i} is a summation vector. These terms are described in more detail in the following paragraphs.

In this model, the vector \mathbf{f} has elements for each commodity produced by the economy. Previous EIO-LCA research (e.g. Horvath and Hendrickson 1998, Facanha and Horvath 2006, Norman et al. 2006) has filled this vector based on the commodities needed to complete a single project or create a single product. For our research, we fill the \mathbf{f} vector with macroeconomic data, such as the total output of each commodity that makes up GDP, or the total value of each commodity imported to the US in a given year.

The U.S. Bureau of Economic Analysis (BEA) publishes 491-sector total requirements matrices (\mathbf{T}) for the U.S. economy every 5 years (BEA 1997), and 65-sector matrices every year (BEA 2006b). In order to perform multi-year analysis, we use the BEA's annual 65-sector industry-by-commodity total requirements matrices for 1998–2004.⁷ This allows us to account for changes in the scale and composition of the US economy over time, but comes at the cost of reduced sectoral resolution.

⁷ The BEA defines this matrix as $\mathbf{T} = \mathbf{W}(\mathbf{I} - \mathbf{B}\mathbf{W})^{-1}$, where \mathbf{W} is an industry-by-commodity matrix showing the proportions of each commodity produced by each industry, and \mathbf{B} is a commodity-by-industry matrix showing the direct inputs of each commodity required to produce a dollar of output from each industry (BEA 2006b).

The diagonal matrix \mathbf{D} holds price deflators to convert gross output from current-year dollars to the equivalent gross output in 1997 dollars. It contains one element for each industry, and there are separate \mathbf{D} matrices for each year. For each year y , the deflator for industry k is defined as $D_k \equiv p_{k,1997} / p_{k,y}$, where $p_{k,y}$ is the gross output price index published by the BEA for industry k in year y (BEA 2006a).

\mathbf{R} is a diagonal matrix showing the environmental impact per dollar of gross output from each industrial sector. There are separate matrices for each type of environmental impact in the model. The \mathbf{R} matrices in our model are based on equivalent matrices used in an on-line version of the EIO-LCA model hosted by the Green Design Institute (GDI) at Carnegie Mellon University (Hendrickson et al. 2006). The GDI matrices are prepared at the 491-sector detailed level of resolution from vectors of total environmental impact at the same resolution. We created 65-sector summary versions of \mathbf{R} by summing environmental impacts across all the detailed sectors included within each summary sector, and then dividing by gross output at the summary level.

Because environmental impact vectors are only available from GDI for 1997, we use the 1997 coefficients for all study years. Thus, our results do not account for technological change that might have occurred within industries between 1998 and 2004. While this is a lacuna, it is reasonable to assume that intra-sectoral environmental technology is constant relative to changes in the scale and composition effects for the short duration of study considered here.⁸

When each \mathbf{R} matrix is multiplied by the gross output (\mathbf{DTf}) for any year, it yields a vector showing the total environmental impact generated in each industry in the course of

⁸ It is generally assumed in the economic literature that the adoption of new environmental technologies is slow without environmental policy or regulation to induce technological change, or without significant reductions in cost (Jaffe et al. 2002, Taylor et al. 2005). There has been little positive inducement for the adoption of pollution abatement and energy efficient technologies in the U.S. between 1998 and 2004; and environmental technologies have low learning rates, which implies their price has not significantly fallen (Rubin et al. 2004).

producing the final outputs \mathbf{f} . For our purposes, it is more useful to know the total environmental impact across all sectors. This total is found by use of a summation vector \mathbf{i} (filled with 1's). Then e is a single-element matrix showing the desired value, which we subsequently treat as a scalar value.

To simplify further discussion of this model, we introduce a row vector $\mathbf{r} \equiv \mathbf{iRDTr}$, with one element for each final demand sector. Then Equation 1 becomes simply

$$e = \mathbf{rf}. \quad (2)$$

The vector \mathbf{r} encapsulates the key relationships of the EIO-LCA model: it shows the total, economy-wide environmental impact induced directly and indirectly per unit of final demand for each commodity. The elements of these vectors can be thought of as the life-cycle environmental intensity for each type of commodity produced by the economy. The dot product of this vector and final demand (\mathbf{f}) gives total environmental impact e . There are different \mathbf{r} vectors for each year and each category of environmental impact.

Returning now to the discussion from the previous section on studying national environmental trends, recall that the production-based approach calculates the total environmental impact that falls inside US borders across years (the national environmental accounts), without accounting for environmental impact embodied in trade. In order to calculate the production-based national environmental accounts using Equation 2, we populate the final output vector (\mathbf{f}) with the values of *all* the goods and services produced in the economy in a given year, broken down by commodity sector. In this case, the vector product of \mathbf{i} and \mathbf{f} equals total US GDP. We define this special case when final output equals the value of all commodities that make up GDP as \mathbf{p} so that we may conveniently refer to GDP in equation form later in the paper. We then calculate the production-based national environmental accounts (e_{prod}) for each

environmental impact, for each year using equation 2. Values for the production-based national environmental accounts are shown for 1998-2004 in Table 1.

IV. Calculating the Balance of Embodied Emissions in Trade

This section describes our method for calculating the balance of embodied emissions in trade (BEET) for the US economy from 1998 to 2004 and presents the results of this calculation under the assumption that commodities have the same environmental intensity whether they are produced in the US or elsewhere.

In Section III, we used the EIO-LCA model to calculate the production-based national environmental accounts (Table 1). These values serve as the baseline from which the shift to a consumption-based approach will be compared. BEET represents the net leakage from this baseline, or the amount of emissions attributable to US consumption that is not accounted for in production-based national environmental accounts. Combining BEET with this baseline provides a consumption-based measure of total US environmental impact that includes impacts embodied in international trade. This is a step that has not been explicitly done before in a life-cycle sense for the US.⁹

Muradian et al. (2002) define BEET as the embodied emissions in imports minus those in exports. Using Equation 2, the vector for final output (\mathbf{f}) is expressed in terms of imports and exports, and we obtain

$$e_{trade} = \mathbf{r}_m \mathbf{m} - \mathbf{r}_x \mathbf{x}. \quad (3)$$

⁹ For similar approaches applied for greenhouse gas emissions for Brazil, Italy and Japan and South Korea, respectively, see Shaeffer and de Sa (1996), Mongelli et al. (2006), and Rhee and Cung (2006).

Here, \mathbf{r}_x and \mathbf{r}_m are the life-cycle environmental intensities of all exported and imported commodities, respectively, \mathbf{x} and \mathbf{m} are vectors showing U.S. exports and imports of each commodity,¹⁰ and e_{trade} gives the value of BEET. Because exports share the same production processes as the rest of U.S. goods and services, the environmental intensity of exports (\mathbf{r}_x) is equal to the environmental intensity of domestic production (\mathbf{r}). A starting assumption for including imports into equation 3 is that of equal sectoral environmental intensity across countries. This holds that the production of a unit of a given good leads to the same amount of environmental impact regardless of where that good is produced in the world. This assumption is commonly made in international input-output analysis. Section VI modifies this assumption to consider the implications for BEET of changing the relationship between import and export environmental intensities. For now, under the assumption of sectoral constancy, the environmental intensity of imports (\mathbf{r}_m) equals the environmental intensity of domestic production (\mathbf{r}) and Equation 3 simplifies to

$$e_{trade} = \mathbf{r}[\mathbf{m} - \mathbf{x}]. \quad (4)$$

Because BEET focuses on emissions and not energy or resource use, we expand BEET to include both emissions and energy use embodied in trade. To derive BEET for each of the environmental impacts under study (GWP, energy, TRI, carbon monoxide, particulate matter < 10 μ m, sulphur dioxide, nitrogen oxides, lead), the trade deficit ($\mathbf{m} - \mathbf{x}$) for each economic sector was multiplied by its corresponding EIO-LCA generated environmental intensity (\mathbf{r}) for all environmental impacts for 1998-2004. Table 2 shows the net BEET for the US economy.

¹⁰ The values of \mathbf{x} and \mathbf{m} are taken from the columns labeled “Exports of goods and services” and “Imports of goods and services” in the BEA’s annual summary-level supplementary use tables (BEA 2006b). Values of \mathbf{m} are converted from negative to positive values for this paper.

Environmental impacts for which the BEET is a net positive indicate cases where more environmental impact is associated with US imports than exports and are thus impacts that have a positive environmental leakage. This corresponds to what we will call “exported environmental impact” or “displaced environmental load” because US consumption creates more pollution than is released within the US alone. In this case, the production-based approach fails to account for the pollution generated outside of US borders to fulfill the final US demand. Similarly, environmental impacts for which there is a negative BEET indicate cases where more environmental impact is associated with US exports than imports, which means that US consumption causes less environmental impact than the quantity that falls within the US. The data in Table 2 show that the US was a net exporter of all of the environmental impacts under study throughout the years of 1998-2004.¹¹

Upon inspecting the contribution of each of the 65 sectors under study to total BEET, we found that BEET for all environmental impacts was highly concentrated in a handful of sectors. The combined BEET of three sectors— primary metals; motor vehicles, bodies, trailers and parts; and oil and gas extraction—makes up more than 50% of the total US BEET for all study years and environmental impacts. If we add the next three sectors that contribute most to BEET—apparel, leather and allied products; chemical products; and computer and electronic products—to the first three, their combined BEET equals more than 85% of total US BEET. The rank of these sectors vary across year and environmental impact, but taken together they are the largest contributors to BEET. These sectors do not necessarily produce the most direct environmental impact; rather, the full supply-chain impacts for final goods from these sectors are

¹¹ It should be noted that TRI is an aggregate measure of all toxic releases and does not account for differences in toxicity between substances. Therefore, the mix of toxic releases between 1998 and 2004 could be quite different even though the TRI value used in EIO-LCA makes no distinction.

the greatest.

Another way to express BEET is in terms of percent leakage. Leakage is defined here as the percentage increase in environmental impact (or environmental intensity) upon the inclusion of BEET:

$$leakage = \frac{e_{trade}}{e_{prod}}. \quad (5)$$

Table 4 shows the results for leakage from production-based approaches to national environmental accounts. These data suggest that leakage was positive and increasing for all of the environmental impacts considered here from 1998 to 2004, with the exception of CO, which showed negligible increase.

Leakage has important implications for the accuracy of national environmental accounts. All environmental indicators are simplified representations of real environmental impact. They thus inherently contain some percentage of leakage, or environmental impact that is either overcounted or, more often, undercounted. Leakage can be based on definitional ambiguity, the use of threshold values under which environmental reporting is not required (as in the TRI), failure to account for all possible sources of environmental impact, or other factors. Although leakage is inevitable, not all forms of leakage are acceptable. Different environmental indicators have different goals and priorities that require different levels of accuracy. For instance, for national greenhouse gas (GHG) inventories, a single percentage of leakage could make a large difference for climate policy, since ongoing policy discussions focus on emission reductions in the range of 10% of the national total. For measures like the TRI, for which industries are only required to report if they use more than 10,000 lbs of any single listed chemical, 1% additional leakage relative to existing accounts may be less significant.

The values presented in Table 4 show that percent leakage increases considerably over time for most of the impacts, with GWP doubling from 4% in 1998 to 8% in 2004, TRI tripling from 5% to 15%, lead rising from 19% to 29%, and PM_{10} more than doubling from 3% to 7%.

V. Resolving leakage into individual effects

This section defines different contributing effects to environmental leakage and uses equations expressed in terms of these effects to explain the behavior of environmental leakage. One way to examine the relationship between trade and leakage is through a measure of the scale effect of trade, which quantifies the extent to which trade increases consumption relative to production. Table 5 shows the trade deficit as a percentage of GDP from 1998 to 2004, one measure of the scale effect. It shows that the scale of trade has been increasing steadily since 1998, with a slight dip in 2001. The increased leakage between 1998 and 2004 shown in Table 4 suggests that as the trade deficit increases relative to GDP, leakage from a production-based approach to environmental indicators will also increase. This makes sense given that the trade deficit represents the value of traded goods accounted for by a consumption-based approach to environmental impact but left out of production-based approaches.

Based on the scale effect alone, it is clear that production-based approaches to environmental trends have historically had relatively low leakage because production and consumption were closely coupled (low absolute balance of trade). However, as trade deficits rise as a percentage of GDP, we would expect leakage to also rise. Indeed, the first quarter of the 21st century is widely projected to see a steady rise in the US trade imbalance. A major caveat to projecting the relationship between trade and leakage into the future is that the trade numbers in

Table 5 do not account in any way for the composition of traded goods. This is demonstrated in Table 4 by the variation in the leakage trends for each environmental impact. For example, leakage of CO does not rise over the study years, despite an intensifying scale effect. Similarly, the fact that the percent leakage for TRI is much greater than the trade deficit as a percentage of GDP suggests the importance of examining the composition of international trade.

To determine how the composition of US trade affects leakage, we now examine the relationship between the environmental intensities of sectors from which we are net exporters versus net importers. The relationship between these intensities is shown by the international terms of trade on environmental impact, or the environmental terms of trade (Antweiler 1996), which is calculated by dividing the average environmental intensity of exports by the average environmental intensity for imports:

$$\tau = \frac{r_x}{r_m}, \quad (6)$$

where r_x and r_m are the average environmental intensities for all exported and imported products, respectively. The average environmental intensity of exports is calculated as:

$$r_x = \frac{e_x}{x} = \frac{\mathbf{r} \cdot \mathbf{X}}{\mathbf{1} \cdot \mathbf{X}}. \quad (7)$$

Here, e_x is the total environmental impact associated with exported commodities, and x is the total economic value of exports from the U.S. We calculate e_x from the vector of exported commodities \mathbf{x} using the standard EIO-LCA approach in Equation 2, and the scalar x is the simple sum of the exported commodities in the vector \mathbf{x} . A similar formulation was used for the average environmental intensity of imports (r_m). These calculations were repeated for each type of environmental impact, for each year of analysis.

Table 6 shows the environmental terms of trade for the impacts evaluated in this study, under the assumption of sectoral constancy.

Values for environmental terms of trade greater than one indicate that more environmental impact is embodied per dollar of revenue from exports than is embodied per dollar of expenditure on imports. More simply put, environmental terms of trade greater than one show that US exports are more environmentally intensive (for the given impact) than imports. Table 6 shows that for all environmental impacts under study, with the exception of VOC and CO, the environmental terms of trade were less than one throughout 1998-2004.¹² This confirms the general assumption that the US imports more environmentally intensive goods than it exports. However, the fact that the terms of trade on VOC and CO are greater than one; and that the terms of trade for all environmental impacts, save TRI, increase from 1998-2004; suggest that this trend may be reversing, rather than intensifying.

Beyond reflecting on broader macroeconomic trends in the environmental intensity of trade, the environmental terms of trade (τ) can be used to explicitly compare the relative contribution of the composition and scale effects to leakage (shown in Table 4). Using the definition of the environmental terms of trade in Equations 6 and 7, BEET (Equation 4) can be expressed as

$$\begin{aligned}
 e_{trade} &= e_m - e_x \\
 &= r_m m - r_x x \quad . \\
 &= r_x \left(\frac{1}{\tau} m - x \right)
 \end{aligned} \tag{8}$$

We can then express leakage (Equation 5) as

¹² It is also interesting to note that environmental terms of trade are lowest for lead and SO₂, which are the most strictly regulated impacts studied here.

$$\begin{aligned}
 leakage &= \frac{e_{trade}}{e_{prod}} = \frac{r_x \left(\frac{1}{\tau} m - x \right)}{r_{prod} P} , \\
 &= \frac{\tau' \left(\frac{1}{\tau} m - x \right)}{p}
 \end{aligned} \tag{9}$$

where p indicates GDP, and we have introduced the variable $\tau' \equiv r_x/r_{prod}$, which compares the average environmental intensity of US exports to the average intensity of all commodities produced in the U.S.¹³ We call this term the relative environmental intensity of exports, which has a unique value for each environmental impact and year.

By inspection of Equation 9, it is apparent that low values of τ (environmental terms of trade) would tend to lead to larger values for environmental leakage. For example, TRI has small values for the environmental terms of trade (τ) (see Table 6) and high leakage values (see Table 4) compared to other environmental impacts. Equation 9 similarly suggests that for large τ values, leakage should be small or negative. However, this effect can be offset by a large trade imbalance. For example, VOC has high τ values (approximately 1.2–1.3) in all years, but leakage remains positive. This is because the ratio of imports to exports (m/x , Table 5) remains even higher than the environmental terms of trade during this period, so that the term in parentheses in Equation 9 always remains positive ($m/x > \tau$, so $m/\tau - x = (x/\tau)(m/x - \tau) > 0$). If the environmental terms of trade (τ) is near one, then leakage is proportional to the scale effect ($m-x$)/ p ; if τ is less than one, then the composition effect enhances the scale effect and increases leakage above the $\tau = 1$ case; and if τ is greater than one, then leakage is reduced from this level.

Although the environmental terms of trade were greater than one and/or rising for many

¹³ Although we assume that each exported commodity has the same environmental intensity as other U.S. production of the same commodity (i.e., $\mathbf{r}_x = \mathbf{r}$), this does not imply that the average intensity of all exported goods (r_x) is equal to the average environmental intensity of all U.S. production (r_{prod}), because exports have a different composition than US production in general.

environmental impacts in 1998-2004, the US trade deficit was so large in this period that the scale effect dominated over the environmental terms of trade, which suggests that leakage is driven by the scale effect.

We now turn our attention to the relative environmental intensity of exports (τ'), which shows the average environmental intensity of exports relative to the average intensity of the US economy. If τ' and the environmental terms of trade (τ) were both one for any environmental impact, then leakage would be governed directly by the scale effect, and leakage would be equal to the ratio of the trade deficit to US GDP (the fifth column of Table 5, also shown as $(m-x)/p$ in Equation 9). We find however that leakage is greater than this ratio in all cases, even above the amount that can be explained by variations in the environmental terms of trade (τ). For example, PM_{10} has τ values close to one during the study years. However, PM_{10} has leakage values (2.6%-6.5%) for the study years that are nearly double the percent trade deficit (1.4%-4.5%). This effect arises because the commodities exported by the U.S. are more intensive for all environmental impacts, in all years, than US production in general. That is to say, the relative environmental intensity of exports (τ'), the values for which are shown in Table 7, is always greater than one.

Because goods produced for export and for domestic consumption have the same environmental intensity at a sectoral level, the difference between the intensity of exports (r_x) and the intensity of domestic production (r_{prod}) is explained entirely by the composition of exported versus domestically consumed commodities. Table 8 allocates total US production and total exports in 2000 between nine coarse sectors. These data show that exports are disproportionately composed of commodities produced in the manufacturing sector, which has environmental intensities much higher than the overall economy. This affirms the idea that traded commodities, which are typically material goods, are more environmentally intensive than

domestically consumed commodities, which are composed of a higher percentage of services. This suggests that environmental leakage will remain persistently higher than the trade deficit or environmental terms of trade (τ) alone would suggest.

VI. Parametric Analysis of Import Intensities

The analysis up to this point has operated under the assumption that environmental intensity is the same for sectors within the US as for those same sectors outside of the US. This, however, is likely a poor assumption. The data requirements to precisely define the average environmental intensity for imports from all economic sectors are far too great given the limited availability of environmental intensities for most countries from which the US imports. A precise consumption-based approach would require the environmental intensity and trade data for all sectors of all countries with which the US trades. This would require a massive disaggregation of foreign economic sectors including input-output tables and industry-based environmental accounts, which are unavailable.¹⁴

While sectoral constancy is likely not an accurate assumption for actual emission outcomes, it could be argued that the US should only be responsible for the amount of environmental impact that would have occurred had imported goods been produced at US environmental intensities. Such an argument would attribute to foreign producers environmental impact embodied in imported goods above that which would have arisen had those goods been produced at US environmental intensities. This framework for responsibility is represented by the assumption of sectoral constancy.

¹⁴ Lenzen et al. (2004) recently advanced an intermediate approach of substituting reasonable CO₂ intensities for the most intensive commodities and trading countries that simplifies these data needs.

The question of how to define the relationship between import and export environmental intensities demonstrates the possibility for differences in how environmental responsibility is defined vis-à-vis environmental impact. For instance, the current production-based approach operates under an implicit assumption of territorial responsibility, which attributes responsibility only for direct emissions within political boundaries (Eder and Narodslawsky 1999, Ferng 2003). A range of different frameworks for responsibility have recently been suggested (see Eder and Narodslawsky 1999, Munksgaard and Pedersen 2001, Ferng 2003). Selecting a framework for environmental responsibility is an inherently political process. While LCA does not explicitly define a framework for environmental responsibility, it is defined as the analysis of the full environmental impacts associated with a product's supply chain and, thus, is inherently a consumption-based measure of environmental impact. To address the full environmental impact of products consumed in the US, regardless of how that impact is allocated in terms of responsibility, requires considering the implications of variation in the relationship between environmental intensities for imports and exports (departing from the assumption of sectoral constancy). This research leaves aside the question of how these impacts are or could be translated into environmental responsibility.

Given the data limitations of a complete consumption-based approach, the next best step is to use parametric analysis to crudely assume that the environmental intensities for all importing sectors are related to US domestic environmental intensities for the same sector by a multiplicative factor. That is, for a given unit of output, imports are assumed to produce a quantity of environmental impact related to US impact by a linear multiplier (s). The multiplier s can be related to the environmental terms of trade (τ) by

$$\tau = \frac{r_x}{sr_m}. \quad (10)$$

Here, r_m is the average life-cycle intensity of imported goods under the assumption of sectoral constancy, and sr_m is the average life-cycle intensity given the sectoral multiplier s . The relationship shown in Equation 10 allows us to consider the implications for leakage given different possible international environmental intensities. To perform this analysis, export intensities (r_x) were held constant, while import intensities (r_m) were uniformly multiplied by s values ranging from 0.5 to 5.0. The reason for holding export intensities constant is that all goods produced domestically, regardless of their location of consumption, have the same environmental intensities. Leakage results for 1998-2004 based on this analysis are shown in Figure 1. The data for leakage presented in Figure 1 show that when imports are two or more times as environmentally intensive as the same commodities produced in the US ($s > 2$), leakage surpasses 10% and shows considerable increases from 1998 to 2004 for all environmental impacts. In the case of TRI and lead, leakage reaches as high as 49% and 85% by 2004, respectively.

This analysis was performed given data limitations on actual import intensities. However, existing literature on environmental intensities for economic production in different parts of the world provides rough approximations on what reasonable s values might be. The US Energy Information Administration reports annual greenhouse gas and energy intensities for most countries in the world (EIA 2006). Multiplying each national intensity by the value of goods imported from that country to the US for the given year, summing across all countries, and dividing by the value of total US imports provides an approximation of what reasonable s values might be for global warming potential (GWP) and energy. From this calculation we find that the

average intensity of imports was 1.6 times that of US production in 1998 and 2.0 times as intensive in 2004 for GWP. Imports were similarly 1.5 times and 1.9 times as energy intensive as US production for the same years.

Data on international environmental intensities for impacts other than energy and GWP are not widely available. Nevertheless, some country specific studies to determine approximate emission intensities have been conducted. Table 9 shows s values derived from Dessus et al. (1994) for three types of toxic release (land, water, air) and the criteria air pollutants, except lead, for five countries: China, Mexico, Japan, Brazil and Indonesia. Dessus et al. used World Bank Industrial Pollution Projection System (IPPS) data combined with input-output tables to evaluate relative pollution intensities across these five countries and the USA. China, Japan and Mexico have been the second, third, and fourth largest exporters to the US for all of the study years, whereas Brazil has ranked between fourteenth and seventeenth and Indonesia between fifteenth and twenty-sixth for the same years (US ITC). In 2004, imports from China, Mexico, Japan, Brazil and Indonesia constituted 13.4, 10.6, 8.6, 1.5 and 0.7 percent of total US imports, respectively.

While the IPSS data shown in Table 9 is not based on actual emissions measurements, it does suggest what reasonable s values might be for TRI and the criteria air pollutants. Here, even Japan, an OECD country, has environmental intensities well over twice those for the US for many environmental impacts. If we extrapolate the environmental intensities for the five countries shown in Table 9 (representing a range of geographic regions and economic structures) over the rough distribution of countries from which the US imports, it becomes clear that s values from 2 to 4 represent the likely range of the actual ratio between US import and export environmental intensities. In the case of TRI in particular, s values of 3 may be considered a

conservative estimate. This provides a guideline for viewing the data presented in Figure 1 and demonstrates that under reasonable assumptions for s , leakage values by 2004 equal or exceed 10% for VOCs ($s = 1.5$), 25% for GWP, energy, PM10, SO2 ($s = 2$), 40% for CO ($s = 3$), and 80% for lead ($s = 2$) and TRI ($s = 3$).¹⁵ Table 10 shows possible values for the sectoral multiplier (s) and the resulting leakage values for each environmental impact under study.

VII. Environmental Kuznets Curve Revisited

In this section we situate the data from the previous sections in the context of the Environmental Kuznets Curve hypothesis. We do so by comparing trends in US per-capita environmental impacts over the period of 1998-2004 under production- and consumption-based environmental approaches. We begin by calculating the annual, per-capita magnitude of each type of environmental impact as

$$c_y = \frac{e_{prod,y} + e_{trade,y}}{pop_y} = \left(\frac{\mathbf{r}(\mathbf{p} + \mathbf{m} - s\mathbf{x})}{pop} \right)_y, \quad (11)$$

where c_y is the per-capita impact of a given type in year y , pop_y is the US population in that year, and other terms are as described above. We performed this calculation for a production-based “no trade” case (\mathbf{m} and \mathbf{x} set to $\mathbf{0}$) and for a consumption-based approach, with sectoral multipliers (s) ranging from 0.5 to 5.0. For easier comparison among these cases, we then calculated the percentage change over time in the per-capita environmental accounts as

¹⁵ While no data were found to approximate s values for lead, a conservative estimate would give lead the same s value as the other criteria air pollutants. However, it is likely that lead emissions in non-OECD countries are even more intensive than other air pollutants relative to the US due, among other reasons, to the slow elimination of lead from gasoline, paints, and solders in much of the world (IOM 1996). For example, 20% of gasoline sales in 1999 were still leaded (UNEP 1999).

$$c'_y = \left(\frac{c_y}{c_{1998}} - 1 \right) \times 100\% . \quad (12)$$

These trends are shown in Figure 2 for TRI emissions, energy use, CO emissions and lead emissions. Table 11 shows the year-by-year trends for every environmental impact in our study, using the sectoral multipliers from Table 10. Figure 2 and Table 10 show a normalized version of the same relationship (per capita emissions versus time) often used to evaluate the Environmental Kuznets Curve (EKC), and can be viewed as a short segment of a longer environmental trend.

Under the “no trade” scenario, per-capita environmental impacts decline, hold approximately steady, or slightly rise over time. However, upon switching to a consumption-based approach, which internalizes environmental impacts embodied in traded goods, and with reasonable assumptions for the sectoral multiplier (s), the overall trend looks quite different: per capita environmental impact rises for all environmental impacts over this 6-year period. As a result, impacts that appear to decline with wealth/time under a production-based approach instead hold steady or rise under a consumption-based approach (e.g. TRI), and impacts that appear to hold steady under a production-based approach instead increase under a consumption-based approach (e.g. energy).

A more detailed analysis of the consumption data and economic linkages used in our model shows that the general upward trend in per-capita environmental impacts over the study period is driven by an even stronger upward trend in per-capita consumption of goods and services. However, this trend is partly masked by steadily increasing efficiency in the economy’s

use of outputs from polluting industries.¹⁶ In 2003-04, growth in consumption outpaced this deintensification, leading to the sharp rise in per-capita environmental impacts for these years shown in Fig. 2.¹⁷

Our research findings, as represented in Table 11 and Figure 2, suggest the possibility that the US has reached an inflection point at which increased wealth leads not to reduced, but rather to increased environmental impact. The implications for such a finding are that if increased trade leads to increases in per capita environmental impact, the inverted “U” will gain an upward sloping “tail.” That is, we might see a turning point for wealthy countries with large trade deficits or trade volumes at which environmental impact per unit of GDP begins to rise based on the impact embodied in net imported goods. Such a late curve inflection point is indeed to be expected based on the consumption-based approach proposed here. This upturn in environmental impact with time/wealth is contrary to what the EKC predicts and may suggest that the typical EKC story—that once a country is on the downward sloping part of the inverted “U,” its environmental impacts necessarily decline with time and/or wealth—may conceal part of the process of economic transformation in wealthy countries.

Previous econometric studies have revealed the contribution of sectoral change in the US economy, rather than technological change, to the “downward” sloping part of the EKC (Suri and Chapman 1998, Cole 2004a). These studies show that some percentage of the decrease in US environmental impact has occurred by displacing environmental load onto other countries through trade, which we have quantified as leakage. Our results confirm these earlier studies’

¹⁶ The deintensification trend can be explained entirely by reductions in the gross output used from the following industries per dollar of GDP, or consumption: Oil and gas extraction; Mining, except oil and gas; Utilities; Petroleum and coal products; Chemical products; Primary metals; Water transportation; Truck transportation; and Waste management and remediation services.

¹⁷ The analysis to determine which industries had declining emissions intensities was conducted by applying 2002 consumption values to the total-requirements matrices, **T**, for each study year.

findings, but for the first time provide life-cycle estimates—rather than modeled econometric estimates—of environmental leakage due to outsourcing.

Our analysis from Section VI, which shows the different effects that drive leakage, has important implications for considering how US consumption-based environmental impacts will change in the future. Our results show that as the trade deficit continues to expand relative to GDP (the scale effect), BEET and percent leakage will likewise increase, as demonstrated between 1998 and 2004. In addition, as long as the environmental intensity of our imports is greater than our exports, BEET will continue to increase as the *total volume* of trade increases, even in the absence of a trade deficit. Therefore, we should expect the predominant production-based approach used in environmental trends analysis today to become increasingly inaccurate as the volume of US imports increases.

While, on first suggestion, a late curve inflection point whereat per capita environmental impacts increase with time/wealth sounds like an extreme critique of the EKC, it actually aligns with the earliest econometric representation of the curve. Grossman and Krueger (1991) studied the relationship between ambient sulphur dioxide concentrations and GDP per capita. They found that above a certain per capita income level, concentrations are estimated to increase with income, suggesting the possibility of an “N-shaped relationship”. Their study explicitly contains variables that account for structural composition of the US economy. While most EKC studies abandon or are puzzled by this late curve upturn of the estimated relationship between growth and environmental impact, the consumption-based approach described here predicts it.

VI. Conclusions

This research has put forth a life-cycle, consumption-based approach to the measurement of aggregate, US environmental impact, with particular attention to the role of trade. The EIO-LCA model was combined with trade data for 1998-2004 to generate a US balance of emissions embodied in trade (BEET) for Global Warming Potential (GWP), energy, TRI, and lead, CO, VOC, NO_x, SO₂, and PM₁₀ emissions. Calculated via a consumption-based approach, the BEET represents net leakage from the predominant method of environmental trends analysis used today, described as the production-based approach in this paper. Section V of this paper compared three different effects that drive leakage: the trade deficit (scale effect), the environmental terms of trade (τ), and the relative environmental intensity of exports (τ'). This section showed that the scale effect explains the overall leakage trend and that τ' enhanced leakage throughout the study years, even for environmental impacts with τ values favorable to low leakage.

This work also quantified the percent leakage of environmental impact from the production-based approach under different scenarios that varied the environmental intensity of our trading partners. Finally, for the same scenarios, we derived consumption-based per-capita environmental impacts.

To highlight some of this study's key findings, we found that given likely ratios of the environmental intensity of US and international economies (described in this paper as s), the US economy had large and growing BEET between 1998-2004 for all environmental impacts. The percent leakage peaked for all impacts in 2004, reaching 10% for VOCs; surpassing 25% for GWP, energy, PM₁₀, and CO; and surpassing 80% for TRI and lead.

Overall, the key conclusions of this research are as follows. Firstly, studies of environmental trends that consider the EKC generally treat the inverted "U" shaped hypothesis

as a starting point. Once countries demonstrate decreasing environmental impact with increasing income, the EKC is taken to be confirmed. The EKC precludes analysis of environmental pathways of wealthy countries that have presumably already environmentally de-intensified. The research presented here suggests the possibility of a “late curve analytics”—a turning point at which environmental impact increases with wealth as environmental impacts are shifted overseas. What may appear to be environmental deintensification in one country could actually mask a net increase in emissions, if production is shifted to trading partners with greater environmental intensity. This signals the need to reopen the question of the relationship between growth and environmental impact for wealthy countries, which is already a hotly contested topic for the South.

Secondly, leakage from production-based approaches to environmental trends analysis has important implications for international environmental policy. As the BEET increases, so too does the gap between environmental impact and current definitions of environmental responsibility. This suggests that the criteria on which national environmental responsibility are based may need to be reevaluated. Otherwise, ambiguities in the relationship between environmental impact and environmental responsibility will make consensus on future international environmental treaties difficult to achieve. Two international environmental conventions are illustrative.

The UN Framework Convention on Climate Change (UN FCCC) bases its estimates of climate change scenarios on national GHG inventories derived from the production-based approach. The Kyoto Protocol calls for a 5-8% reduction in 1990 GHG emissions for Annex 1 countries, mostly in the North. Leakage from national inventories, therefore, has crucial implications for how environmental policy is formulated and for how countries are evaluated vis-

à-vis climate change mitigation commitment paths. Leakage for GWP of more than 10% might significantly alter perceptions of a country's path to climate change mitigation.

Under the assumption of sectoral constancy, leakage for GWP reached 8% by 2004. Assuming an import intensity twice that of domestic GWP intensity, the consumption-based approach put forth here finds that US leakage reached 26% the same year. In the context of climate change policy, this has at least two important implications. First, given the ability of the North (Annex 1) to outsource carbon intensive production activities to the South (non-Annex 1), production-based approaches are inherently biased in favor of countries that have already "developed." Second, because climate change is a problem of the global commons, the free rider effect and the perceived economic risks of early agreement to binding GHG commitments means that uncertainty about the system of accounting or perceived loopholes in the rules of accounting may dissuade countries from committing to GHG targets. Signatory countries to the UN FCCC have expressed deep concerns over "hot air" in emission reduction credits for the former Soviet Union. Similar debates could emerge were leakages from the current production-based approach recognized to be greater than 10% of Annex 1 GHG inventories, which the present research suggests is, indeed, the case.

In 1995, the Basel Convention on the transboundary movement in hazardous waste added a Ban Amendment, which prohibits the export of hazardous materials (of which TRI is a main component) from OECD and EU countries to all other Parties to the Convention (the South). The Basel Convention was widely seen as a crucial step to eliminating the dumping of hazardous wastes on poor countries, or what has popularly been dubbed "toxic trading." It does not, however, address hazardous materials embodied in traded goods. Thus, the outsourcing of a chemicals plant, for example, is entirely legal, whereas the export of the hazardous wastes

produced from that chemical plant prior to outsourcing is not. A key point to note is that OECD countries (not including the US) in the 1990s exported approximately 2% of their total generated hazardous waste (O'Neill 2000). While the Convention certainly reduced what had previously been a higher percentage of traded waste, the current extent to which wastes are regulated by Basel is quite low. Table 4 and Figure 1 show that leakage for TRI is well above 2% for all years of study under the assumption of sectoral constancy, and ranges from 33 to 49% for 1998-2004 when import intensities are assumed to be twice those for the US, which is a very conservative estimate.

The specific reason for the Basel Convention's ban on the export of hazardous waste from the North to the South is because of the poorer disposal options and generally higher risk of harm to human health and environmental quality resulting from materials disposal in the South. There is little reason to believe that the same hazardous materials arising from production processes in the South are disposed of any more safely than when they are directly imported from the North. The data above on leakage of TRI suggests that the hazardous materials associated with the production of goods for foreign consumption is increasingly "leaked" from current analyses of environmental trends. This research suggests that to truly achieve the goals of the Basel Convention and to understand where wastes are being generated and disposed of and for whom, a consumption-based approach to environmental accounting is necessary.

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Tables

Table 1
U.S. production-based national environmental accounts

Year	Environmental impact								
Year	GWP* (TgCO ₂ e)	Energy (PJ)	TRI (Gg)	SO ₂ (Gg)	NO _x (Gg)	VOC (Gg)	PM ₁₀ (Gg)	Lead (Mg)	CO (Gg)
1998	5,410	64,086	7,110	15,230	16,890	7,182	2,770	3,152	42,614
1999	5,484	64,911	7,127	15,100	17,240	7,460	2,833	3,206	44,609
2000	5,661	66,962	7,118	15,666	17,754	7,628	2,875	3,179	45,729
2001	5,531	65,042	6,908	15,122	17,399	7,406	2,813	2,958	44,140
2002	5,690	67,032	6,943	15,787	17,783	7,424	2,832	3,035	44,372
2003	5,680	66,660	6,846	15,486	17,851	7,421	2,850	3,012	44,137
2004	5,835	68,759	7,075	15,708	18,454	7,744	2,917	3,172	46,520

* global warming potential, in units of teragrams (million metric tons) of CO₂ equivalent

Table 2
U.S. Balance of Emissions Embodied in Trade

Year	Environmental impact								
Year	GWP (TgCO ₂ e)	Energy (PJ)	TRI (Gg)	SO ₂ (Gg)	NO _x (Gg)	VOC (Gg)	PM ₁₀ (Gg)	Lead (Mg)	CO (Gg)
1998	233	2,306	370	818	390	33	73	611	1,610
1999	320	3,059	720	990	370	29	129	701	729
2000	383	3,889	821	1,209	519	94	146	814	987
2001	369	3,892	772	1,144	511	133	142	760	1,020
2002	397	4,079	825	1,187	619	216	157	739	1,422
2003	400	4,216	839	1,173	606	222	156	691	1,388
2004	466	4,930	1,072	1,384	719	262	191	923	1,906

Table 3
U.S. consumption-based national environmental accounts (per capita)

Year	Environmental impact								
Year	GWP (MgCO ₂ e)	Energy (GJ)	TRI (kg)	SO ₂ (kg)	NO _x (kg)	VOC (kg)	PM ₁₀ (kg)	Lead (g)	CO (kg)
1998	20.4	240.5	27.1	58.1	62.6	26.1	10.3	13.6	160.2
1999	20.8	243.4	28.1	57.6	63.1	26.8	10.6	14.0	162.3
2000	21.4	251.1	28.1	59.8	64.8	27.4	10.7	14.2	165.5
2001	20.7	241.8	26.9	57.1	62.8	26.4	10.4	13.0	158.4
2002	21.1	246.9	27.0	58.9	63.9	26.5	10.4	13.1	159.0
2003	20.9	243.7	26.4	57.3	63.5	26.3	10.3	12.7	156.5
2004	21.5	250.9	27.7	58.2	65.3	27.3	10.6	13.9	164.9

Table 4
Percent leakage from production-based national environmental accounts

Year	Environmental impact								
	GWP	Energy	TRI	SO2	NOx	VOC	PM10	Lead	CO
1998	4.3%	3.6%	5.2%	5.4%	2.3%	0.5%	2.6%	19.4%	3.8%
1999	5.8%	4.7%	10.1%	6.6%	2.1%	0.4%	4.6%	21.9%	1.6%
2000	6.8%	5.8%	11.5%	7.7%	2.9%	1.2%	5.1%	25.6%	2.2%
2001	6.7%	6.0%	11.2%	7.6%	2.9%	1.8%	5.1%	25.7%	2.3%
2002	7.0%	6.1%	11.9%	7.5%	3.5%	2.9%	5.6%	24.4%	3.2%
2003	7.0%	6.3%	12.3%	7.6%	3.4%	3.0%	5.5%	22.9%	3.1%
2004	8.0%	7.2%	15.2%	8.8%	3.9%	3.4%	6.5%	29.1%	4.1%

Table 5
U.S. trade balance (1997 \$)

Year	GDP (\$B)	Imports (\$B)	Exports (\$B)	Trade	
				Deficit (% GDP)	Imports/ Exports
1998	8,712	902	780	1.4%	1.16
1999	9,134	998	791	2.3%	1.26
2000	9,490	1,155	847	3.2%	1.36
2001	9,521	1,064	778	3.0%	1.37
2002	9,704	1,068	744	3.3%	1.44
2003	9,986	1,136	758	3.8%	1.50
2004	10,447	1,289	824	4.5%	1.57

Table 6
U.S. environmental terms of trade ($\tau=r_v/r_m$)

Year	GWP	Energy	TRI	SO2	NOx	VOC	PM10	Lead	CO
1998	0.83	0.89	0.94	0.73	0.93	1.12	0.96	0.69	0.89
1999	0.81	0.91	0.83	0.72	1.04	1.23	0.92	0.69	1.14
2000	0.83	0.92	0.86	0.73	1.05	1.27	0.96	0.71	1.19
2001	0.82	0.90	0.85	0.72	1.04	1.23	0.95	0.71	1.18
2002	0.82	0.92	0.84	0.72	1.03	1.20	0.95	0.74	1.17
2003	0.86	0.94	0.87	0.74	1.08	1.25	1.00	0.78	1.22
2004	0.87	0.97	0.87	0.75	1.10	1.29	1.00	0.75	1.22

Table 7

U.S. relative environmental intensity of exports ($\tau^i = F_x^i / r_{prod}^i$)

Year	GWP	Energy	TRI	SO2	NOx	VOC	PM10	Lead	CO
1998	1.25	1.37	2.48	1.04	1.05	1.68	1.47	3.15	1.39
1999	1.21	1.38	2.21	1.02	1.14	1.80	1.39	3.05	1.69
2000	1.19	1.36	2.21	0.99	1.12	1.81	1.38	3.14	1.70
2001	1.23	1.42	2.25	1.03	1.16	1.89	1.42	3.40	1.80
2002	1.22	1.41	2.19	0.97	1.15	1.93	1.43	3.34	1.82
2003	1.24	1.42	2.23	0.98	1.15	1.95	1.46	3.29	1.81
2004	1.27	1.46	2.40	1.02	1.18	1.97	1.46	3.37	1.81

Table 8
Share of 2000 U.S. GDP and exports from each major sector (%)

Sector	GDP	Exports	Imports
Agriculture, forestry, fishing, hunting	0%	2%	2%
Mining, utilities and construction	9%	1%	9%
Manufacturing	15%	65%	87%
Trade and transportation	15%	15%	0%
Information, finance, real estate, professional services	24%	17%	2%
Education, health care and social services	12%	0%	0%
Arts, entertainment, accommodation and food services	5%	0%	0%
Other services	4%	0%	0%
Government	15%	0%	0%

Table 9
Environmental intensity for select country/US environmental intensity*

Environmental Impact	Country				
	Indonesia	China	Brazil	Japan	Mexico
Toxic (Air)	2.0	2.3	4.3	2.5	3.3
Toxic (Water)	3.0	4.3	3.8	1.5	1.3
Toxic (Land)	3.0	3.0	5.3	3.0	5.0
SO ₂	3.5	2.0	5.0	2.3	1.0
NO ₂	3.5	2.0	5.0	2.3	1.0
CO	0.8	3.5	5.0	2.3	2.5
VOC	1.0	1.2	4.8	1.8	2.2
PM	3.3	2.8	4.8	2.3	1.0

* "Air", "water" and "land" designate the medium into which toxics are emitted; data reproduced from Dessus et al. (1994)

Table 10
Leakage under varying intensity assumptions for imports [leakage% (s)]

Year	GWP	Energy	TRI	SO ₂	NO _x	VOC	PM10	Lead	CO
1998	13% (1.6)	12% (1.5)	60% (3)	20% (2)	14% (2)	8% (1.5)	18% (2)	67% (2)	36% (3)
1999	15% (1.6)	14% (1.5)	69% (3)	22% (2)	14% (2)	8% (1.5)	21% (2)	70% (2)	34% (3)
2000	17% (1.6)	16% (1.6)	74% (3)	24% (2)	16% (2)	10% (1.5)	22% (2)	79% (2)	37% (3)
2001	17% (1.6)	17% (1.6)	70% (3)	24% (2)	15% (2)	10% (1.5)	22% (2)	79% (2)	36% (3)
2002	18% (1.7)	17% (1.6)	69% (3)	23% (2)	16% (2)	12% (1.5)	22% (2)	74% (2)	37% (3)
2003	21% (1.8)	20% (1.8)	71% (3)	23% (2)	16% (2)	12% (1.5)	22% (2)	71% (2)	37% (3)
2004	26% (2.0)	24% (1.9)	83% (3)	26% (2)	17% (2)	13% (1.5)	25% (2)	85% (2)	41% (3)

Table 11
Change in per-capita environmental impact relative to 1998 (%)

Year	GWP		Energy		TRI		SO ₂		NO _x		VOC		PM10		Lead		CO	
	no trd	trade	no trd	trade	no trd	trade	no trd	trade	no trd	trade	no trd	trade	no trd	trade	no trd	trade	no trd	trade
1998	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0	+0.0
1999	+0.2	+2.1	+0.1	+1.8	\$0.9	+4.4	\$2.0	\$0.5	+0.9	+1.0	+2.7	+2.9	+1.1	+3.5	+0.6	+2.4	+3.5	+2.0
2000	+2.4	+6.0	+2.2	+5.9	\$2.0	+6.5	+0.6	+4.2	+2.9	+4.4	+3.9	+5.6	+1.6	+5.0	\$1.3	+5.9	+5.0	+5.5
2001	\$1.0	+2.5	\$1.7	+2.4	\$5.9	+0.1	\$3.8	\$1.0	\$0.2	+0.9	\$0.1	+1.9	\$1.7	+1.1	\$9.1	\$2.6	+0.3	+0.4
2002	+0.9	+5.3	+0.3	+4.5	\$6.4	\$1.0	\$0.6	+1.4	+0.9	+2.5	\$0.9	+2.4	\$2.0	+1.0	\$7.7	\$3.7	\$0.2	+0.8
2003	\$0.3	+6.8	\$1.3	+5.5	\$8.6	\$2.5	\$3.5	\$1.4	+0.3	+1.7	\$1.9	+1.4	\$2.3	+0.6	\$9.3	\$7.2	\$1.7	\$1.2
2004	+1.4	+13.4	+0.9	+11.8	\$6.4	+7.2	\$3.0	+1.5	+2.7	+5.5	+1.4	+5.7	\$1.0	+4.2	\$5.4	+4.7	+2.6	+6.1