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Input - Output & Environment

SEVILLE (SPAIN)
July 9 - 11, 2008
http://www.upo.es/econ/IIOMME08

Estimating Carbon Footprints with Input-Output Models

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Abstract

Many companies and organizations are pursuing 'carbon footprint' projects to estimate their own contributions to global climate change. Many of these activities rely on definitions from carbon registries and/or greenhouse gas emission estimation protocols that help these organizations analyze their footprints. The scopes of these protocols vary, but they generally estimate: (1) direct emissions, (2) emissions from direct energy use, and (3) other indirect emissions, with a focus on the first and second categories. Few organizations are pursuing the broadest scope boundaries including a full range of their supply chain emissions. In contrast, environmental input-output based life cycle assessment (LCA) methods have long been available to track total emissions across the entire supply chain. Our prior LCA experience suggests that narrowly defined estimation protocols will lead to large underestimates of carbon emissions. If baseline carbon footprints are done with narrow boundaries and the carbon emissions inventory boundaries are later expanded to reflect more indirect emissions, then firms may feel that the protocols are a moving target, undermining the momentum of carbon management (and mitigation) efforts. Also, without a full knowledge of their footprints, firms will be unable to pursue cost-effective carbon mitigation strategies. We offer several case studies to show the importance of setting the right boundaries in advance.

1. Introduction

After years of discussion and warning from scientists around the world, and a fourth assessment report by the Intergovernmental Panel for Climate Change (2007), groups around the world are now considering the extent of their carbon emissions, often called their 'carbon footprint,' and means to reduce these emissions. Since carbon footprinting is a new procedure, it is understandable that there is confusion about the appropriate means and boundary to adopt for these impact analyses. In the US, The Climate Registry (TCR) is a common resource (2007). TCR requires firms to report all direct emissions[1] from their facilities and company vehicles as well as purchases of electricity, steam, heat and cooling in conducting an audit of carbon emissions. TCR suggests reporting of emissions for each of the Kyoto Protocol greenhouse gases: carbon dioxide (CO_2), Nitrous Oxide (N_2O), Methane (CH_4), Hydrofluorcarbons (HFCs), Perfluorcarbons (PFCs), and Sulfur Hexafluoride (SF_6), although TCR allows firms to begin with just carbon dioxide emissions.

Similar to TCR, the World Resources Institute / World Business Council for Sustainable Development (WRI/WBCSD) have developed a greenhouse gas (GHG) protocol with a supporting website to help organizational footprint efforts (2007). This reporting protocol defines three 'scopes' of carbon footprints: (1) direct emissions, (2) indirect emissions due to purchase of electricity, and (3) other indirect emissions. Many other organizations, such as firms and NGOs that sell carbon offsets, also have protocols to help draw boundaries around the types of activities that should be explored when estimating carbon footprints. Beyond the registry hosts, many large and startup companies have formed to assist companies in developing and managing their carbon footprints – many of them using input-output methods.

These registry or protocol entities generally define carbon footprint inventories in increasingly bigger scopes or "tiers". The "Tier 1" definition usually consists of the direct emissions of the organization itself (e.g., the carbon dioxide emissions coming out of a firm's factories and vehicles). "Tier 2" typically expands the boundary to include the emissions of energy inputs used by the organization. The final tier then

[1] The definition of "direct" in this domain is different than that of the input-output community (and leads to some forms of confusion), and is discussed later in the text.

typically expands the boundary to include "other indirect activities", which is quite vaguely defined in general but presumably suggests adding in other known sources of GHG emissions for an industry. This final tier is defined very differently but in general does not include "all" indirect activities, but instead lists various categories of interest.

We consider how inclusive the tiers as defined above might be for a firm. That is, if firms were to follow the guidance set by these protocols, how much of their total carbon footprints would they capture? Do these limited carbon footprint estimates provide reasonable guidance for firms in managing their supply chains?

2. Methods

2.1 Input-Output Life Cycle Assessment

We leverage input-output life cycle assessment (IO-LCA) methods that track all activities across the supply chain for a specific industry to answer these questions. While IO theory is old, its application was limited for decades by data availability (*i.e.*, carbon emission estimates for all sectors in the economy).

In this analysis, we use a specific implementation of an input-output model for the US economy, the Economic Input-Output Life Cycle Assessment (EIO-LCA) method developed at Carnegie Mellon University (2008), with the full model freely available online at www.eiolca.net and as described by Hendrickson (2006). Within the LCA community, it has been used more than a million times to estimate life cycle and supply chain environmental impacts, e.g., GHG emissions. Note that EIO-LCA (and other IO-LCA / LCA models) typically contains estimates of flows for many items beyond GHG emissions, such as releases of conventional pollutants and toxics, hazardous wastes, energy use, etc. In this research, we use the 1997 industry-by-industry benchmark model of the US economy that contains 491 industry sectors (which we will refer to as the "1997 EIO-LCA model").

The purpose of developing carbon footprints is also discussed. We argue that the footprints should be used by firms to pursue more effective greenhouse gas mitigation policies. As a corporation can influence their suppliers, a broader estimation can similarly motivate more effective corporate climate change policies.

2.2 Formal Equations for Footprint Tier Estimation

In this section, we develop equations to estimate 3 tiers of carbon footprints estimates:

- Tier 1 includes direct emissions from a sector, including emissions from natural gas and petroleum combustion.
- Tier 2 includes emissions due to electricity and steam purchases for a sector.
- Tier 3 includes the total supply chain of emissions.

The emission equation development uses some linear algebra that is common in the literature of IO-LCA methods.

Algebraically, the required economic purchases in all sectors of the US economy required to make a vector of desired output y (which is a list of the sector final demands) can be calculated as (adapted from Blair and Miller (1985)):

$$x = (I + A + A*A + A*A*A + ...)\, y = (I - A)^{-1}\, y \quad \textbf{(1)}$$

where x is the vector (or list) of required inputs, I is the identity matrix, A is the input-output total requirements matrix (with rows representing the required inputs from all other sectors to make a unit of output for that row's sector) and y is the vector of desired output. For example, Eq. 1 might be applied to represent the various supply chain requirements for producing electricity or natural gas purchased by residences. In Eq. 1, the terms represent the production of the desired output itself (I*y), contributions from the direct or first level suppliers (A*y), the second level indirect suppliers (A*A*y), etc. The infinite series of the supply chain can be replaced by $(I-A)^{-1}$ (where the $^{-1}$ indicates multiplicative inverse). Using Eq. 1, we estimate the outputs required throughout the economy to produce a specified set of products or services. The total of these outputs is often called the "total supply chain" for the product or service, where the "chain" is the sequence of suppliers. The input-output model includes all such chains within the linear model in Eq. 1.

Once the economic output for each sector is calculated, a vector of direct environmental emissions can be estimated by multiplying the output at each stage by the environmental impact per dollar of output:

$$\mathbf{b_i = R_i x = R_i(I - A)^{-1} y} \quad \textbf{(2)}$$

where b_i is the vector of environmental burdens (e.g., greenhouse gas emissions for each sector), and R_i is a matrix with diagonal elements representing the emissions per dollar of output for each sector.

With this economic input-output background, we can formalize the tier calculations for greenhouse gas protocols. The Tier 1 direct emissions would be:

$$\mathbf{b_i = R_i(I)y = R_i y} \quad \textbf{(3)}$$

where y is a vector with output from the sector of interest and zero elsewhere. Note that the economic input-output model represents emissions from an economic sector rather than an individual firm. To estimate firm emissions, the difference between the firm's emission rate and the industry sector's average rate should be included. The Tier 2 emissions including energy purchases would be calculated as:

$$\mathbf{b_i = R_i(I + A')y} \quad \textbf{(4)}$$

where A' is a truncated requirements matrix including only industry sectors providing energy inputs to the sector, such as power generation or steam. A full (Tier 3) supply chain including indirect emissions would result from applying Eq. 2 to the sector output.

3. Results

2.1 Comparison of Tier 1, Tier 2 and Tier 3 Carbon Footprints

Using the 1997 EIO-LCA model, we find that the first 2 tiers of the carbon footprint protocols include only a small fraction of the total supply chain footprint for most industries. In short, carbon footprint guidelines that focus on a firm's direct emissions and purchases of energy in general miss the majority of GHG emissions for a majority of industries.

In contrast to the sectors for which total carbon footprints far exceed Tier 1 and Tier 2 emissions, the 10% of sectors that would have most of their footprint (80+%) represented by Tiers 1 and 2 are well-known sources such as power generation, cement manufacturing, and the transportation sectors (air, truck, rail, and water). This is relevant because sectors with large and known carbon footprints are already aware of their emissions (and more importantly, so are agencies such as EPA and DOE). Other sectors of the economy are just beginning to think about their footprints. Decision makers in those sectors would not be well-served by using the broadly promoted protocols to estimate their total carbon emissions.

To help explain some of the specific reasons behind how much of an industry's footprint would be estimated by the existing protocols, we provide several case studies, the results of which are summarized in Table 1. We also present the fraction of total carbon emissions represented by Tier 1 (sector direct emissions) and Tier 2 (sector energy inputs) relative to the total supply chain emissions for a sector. For the average sector, only a quarter of the total supply chain emissions are represented by the Tier 1 and 2 emissions.

Table 1

Case Study 1 – The US Postal Service

The US Postal Service (USPS) is the world's largest shipper of mail, and operates a fleet of thousands of vehicles and constructed facilities across the US. Over the last decade, USPS has made public efforts to reduce its footprint by moving to more use of alternative fuels like biodiesel and ethanol in its fleet. The emissions of its Tier 1 activities (e.g., driving its fleet of vehicles) are on the order of 26 mt CO_2 (per $million of output). Its emissions from their energy purchases are 7 / $million. However USPS still outsources significant freight movement to trucking and air companies (e.g., UPS, FedEx, and commercial air carriers), the sum of which are far greater than its Tier 1 or Tier 2 emissions. Thus, a focus on those tiers would overlook by far the greatest sources of USPS' footprint. Likewise, any carbon mitigation policies that focused on alternative fuels for its vehicles would have limited effect – e.g., completely eliminating CO_2 emissions from its fleet would eliminate only about 10% of its total footprint.

Case Study 2 – Book Publishers

Book publishers are another sector with relatively low Tier 1 and Tier 2 emissions relative to their total footprint. With supply chains involving substantial manufacturing for inputs such as paper and considerable transportation, the Tier 1 and 2 carbon footprint is only 6% of their total. Another consideration for book publishers' carbon footprint are the emissions associated with delivery, either through personal vehicle trips or package delivery services (e.g., by Matthews et al. (2000); Matthews et al. (2001).

Case Study 3 – Power Generation

The power generation and supply sector is a known major source of GHG emissions. It is their own direct emissions (e.g., from burning fossil fuels) that by and large comprise their footprint, with 92% of their total emissions in Tier 1. This is an industry whose footprint can be fairly accurately estimated with the tier 1 boundary. However, the delivery of fuels to power plants still represents a significant source of GHG emissions (e.g., rail deliveries of coal and natural gas pipelines).

Case Study 4 – Paint and Coatings

This industry (as well as the chemical industry in general) is being asked to pursue "bio-based feedstocks" to substitute known use of fossil fuel feedstocks. However, only 14% of its GHG emissions come from Tier 1 and Tier 2 sources. Thus investing in bio-based feedstocks would mean billions of dollars of commitment per company, and have relatively small effect on its total footprint. There would be larger mitigation opportunities from encouraging green energy procurement throughout its supply chain (and be much less expensive).

4. Implications

Carbon footprints can be used for a variety of purposes, and surely, the method used to calculate them should reflect these differing uses. The broadest carbon footprint definition above, that of Tier 3, is intended to aid effective management strategies. Similarly, consumers have some influence over the carbon footprints of goods and services through their purchase decisions. Without quantitative indicators of total carbon footprints, these decisions on the part of consumers and firms would be less effective, since they would not be telling the whole story.

Nevertheless, consumers' influence over their total carbon footprints and businesses' influence over their supply chains should not be overstated. For instance, should a consumer be responsible for the electricity purchases of an aluminum producer far down the supply chain of producing an iPod? Should Apple be held responsible for these purchases and thus account for them in its own footprint? What about the aluminum producer itself?

It is clear that in the case of any complicated product, any number of different players in the supply chain could claim responsibility for the emissions associated with producing materials, basic chemicals, and other low-value-added goods which end up embedded in final consumer goods. If it is desirable to achieve total GHG accounting without double-counting, multiple counting of responsibility is problematic. This confusion has led some to suggest systems of sharing responsibility between different members of supply chains (Lenzen 2007). Lenzen has shown (2007) that a consistent and comprehensive way to assign total GHG emissions to different producers and consumers without double-counting.

However, there are problems with responsibility sharing for carbon footprints. The most important problem is that many firms produce many different products, all of which have different supply chains, and sharing responsibility with both their suppliers and their consumers for all these products would likely lead to a harrowing accounting task. Even if it could be overcome, it is unlikely many firms would spend the necessary time and money to understand and calculate this type of footprint. If calculating footprints remains voluntary for firms, simplicity must be valued highly in the design of protocols. It is probably for reasons similar to these that the original protocols for carbon footprinting were written from a firm, instead of a product, perspective. Despite these concerns, issues like double-counting are only a problem when participation in calculating footprints gets to a much higher degree than currently exists or comprehensive regulation is imposed.

5. Conclusions

Many organizations are already pursuing carbon emission inventory projects to begin considering their baseline carbon footprints, in preparation for future carbon mitigation projects. Many of these groups are also looking to the protocols for guidance in how to prepare their footprint inventories. As such, our results suggest that these protocols in general will lead the organizations to footprint estimates that are relatively small in comparison to their total footprints. This effect will likely lead to firms making mitigation decisions that are short-sighted.

In developing broad measures of carbon footprints, international trade should also be included. With growing international freight and greater production in countries with lower environmental regulatory requirements and higher carbon intensities, total carbon footprints should reflect the emissions due to this transport and overseas production. The input output life cycle assessment framework can be extended to estimate such international emissions (Weber 2007). It may be useful to distinguish different scopes for the Tier 1, 2 and 3 footprints to reflect emissions in particular areas to promote better carbon management.

Finally, we expect that other environmental and energy components will become popular "footprint" targets in the future, such as water and fossil fuels. The results here could be applied to those domains and have similar results.

Acknowledgements

We thank the Green Design Institute Industrial Consortium at Carnegie Mellon University, EPA STAR Graduate Fellowship, and the National Science Foundation (NSF) grant #06-28232. The opinions expressed herein are those of the authors and not of the NSF.

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Table 1

	Tier 1 * (% of total)	Tier 2 * (% of total)	Tier 1 + 2 * (% of total)
Postal Service	10	3	13
Book Publishers	5	1	6
Power Generation	92	1	93
Paint / Coatings	11	3	14
Average Sector	14	12	26

Carbon Footprint Estimates for Protocol Tier and Total Emissions

* Note that row totals may not sum exactly due to rounding.