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Viewpoint

The Importance of Carbon Footprint Estimation Boundaries

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Because of increasing concern about global climate change and carbon emissions as a causal factor, many companies and organizations are pursuing "carbon footprint" projects to estimate their own contributions to global climate change. Protocol definitions from carbon registries help organizations analyze their footprints. The scope of these protocols varies but generally suggests estimating only direct emissions and emissions from purchased energy, with less focus on supply chain emissions. In contrast, approaches based on comprehensive environmental life-cycle assessment methods are available to track total emissions across the entire supply chain, and experience suggests that following narrowly defined estimation protocols will generally lead to large underestimates of carbon emissions for providing products and services. Direct emissions from an industry are, on average, only 14% of the total supply chain carbon emissions (often called Tier 1 emissions), and direct emissions plus industry energy inputs are, on average, only 26% of the total supply chain emissions (often called Tier 1 and 2 emissions). Without a full knowledge of their footprints, firms will be unable to pursue the most cost-effective carbon mitigation strategies. We suggest that firms use the screening-level analysis described here to set the bounds of their footprinting strategy to ensure that they do not ignore large sources of environmental effects across their supply chains. Such information can help firms pursue carbon and environmental emission mitigation projects not only within their own plants but also across their supply chain.

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Introduction

After years of discussion, a fourth assessment report by the Intergovernmental Panel on Climate Change (*1*), and increasing requirements from retailers and shareholders, firms around the world are now considering the extent of their carbon emissions, often called their "carbon footprint," and the means to reduce these emissions (*2*). Companies increasingly understand that global carbon emissions regulation, likely in an emissions-trading system, is imminent. Because carbon footprinting is a new procedure, it is understandable that there is confusion about the appropriate means and boundaries to adopt for these impact analyses.

The definition of "carbon footprint" is surprisingly vague given the growth in the term's use over the past decade. The term itself is rooted in the literature of "ecological footprinting" (*3*): attempting to describe the total area of land needed to produce some level of human consumption. Because the land use to make most consumer products is fairly distant in time and space from the final consumer, the ecological footprint is inherently a full life-cycle calculation. However, this does not seem to be true for the term's new successor, the carbon footprint; Wiedmann and Minx (*4*) found a large variety of definitions that differ in which gases are accounted for, where boundaries of analysis are drawn, and several other criteria.

In the United States, the California Climate Action Registry (CCAR) and, more recently, The Climate Registry (TCR) are common resources for defining and calculating carbon footprints (*5*). CCAR/TCR require firms to report all direct emissions from their facilities and company vehicles as well as purchases of electricity, steam, heating, and cooling. They suggest reporting emissions for each of the Kyoto Protocol greenhouse gases (GHGs): carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6), although CCAR allows firms to begin with just CO_2 emissions. Similarly, the World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD) have developed a GHG protocol with a supporting Web site to help organizational footprint efforts (*6*).

Most protocols, including the WRI/WBCSD, define carbon footprint inventories in increasingly bigger scopes or "tiers". The "Tier 1" definition consists of the direct emissions of the organization itself (e.g., the CO_2 emissions coming out of a firm's factories and vehicles). "Tier 2" expands the boundary to include the carbon emissions of energy inputs used by the organization, given that the energy sector is a leading source of GHG emissions. An optional final tier expands the boundary to include "other indirect activities", which is vaguely defined in general but presumably suggests adding in other known sources of GHG emissions for an industry. In this analysis, 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, i.e., total life-cycle emissions, would they capture? Do the Tier 1 and 2 estimates provide reasonable guidance for firms in managing their supply chains?

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To answer these questions, we leverage existing environmental life-cycle assessment (LCA) models, specifically input−output LCA (IO-LCA) methods that track all activities across the supply chain for a specific industry. Economic input−output models were first proposed by Leontief in 1936 (*7*) to aid in manufacturing planning. The models estimate all purchases and activities in a supply chain leading up to final manufacture in an industry. They have a very broad boundary, including all activities in an economy. Although IO theory is old, its application was limited for decades by limited computing power and data availability (i.e., carbon emission estimates for all sectors in the economy). Here we utilize a specific implementation of an input−output model for the U.S. economy, the 1997 Economic Input−Output Life Cycle Assessment (EIO-LCA) method developed at Carnegie Mellon University, with the full model freely available online at www.eiolca.net (*8, 9*). 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. For life-cycle assessment studies, the basic economic input−output model is often augmented with impact data for specific goods, services, and organizations, rather than by using average economic sector data; the resulting analysis is termed “hybrid analysis” (*8, 10*).

We argue that the footprints should be useful in pursuing more effective climate change policies. However, the information contained in a carbon footprint varies depending on how it was calculated and how much responsibility the entity being “footprinted” is willing to take on. There is an inherent trade-off between comprehensiveness (i.e., the percentage of total world GHG emissions included in a system) and participation (i.e., the percentage of businesses or consumers taking part in the system). Because consumers can influence the carbon footprints of goods and services through their purchase decisions, a broad estimation of carbon footprints including supply chain effects is appropriate. Similarly, as a corporation can influence its suppliers, a broader estimation can similarly motivate more effective corporate climate change policies.

However, there is a limit to the extent to which final consumers and even intermediate businesses can affect emissions occurring far up the supply chain. Thus, a balance must be made, and consistent, comprehensive rules must be developed to decide the proper extent of inclusion for supply chain GHG emissions. Possibilities and tradeoffs are discussed below.

Economic Input−Output Life-Cycle Assessment Estimation of Carbon Footprints

We develop estimation equations for three tiers of carbon footprint estimates for all economic sectors in the U.S. economy:

- Tier 1 includes direct emissions from a sector, including emissions from natural gas and petroleum combustion. This is similar to the “producer perspective” (*11*) used for emissions inventories of countries, states, etc.
- Tier 2 includes emissions due to electricity and steam purchases for a sector.
- Tier 3 includes the total supply chain up to the production gate, also known as cradle-to-gate, emissions.

The emission equation development uses some linear algebra that is common in the literature of economic IO-LCA (*8*). Here we explain the application of the model to carbon footprinting; more detailed development is available elsewhere (*7, 8*).

The basic input−output model derives the total economic purchases (i.e., supply chain) across an economy required to make a vector of desired output **y**, commonly called “final demand”:

TABLE 1. Summary of Carbon Footprint Estimates for Protocol Tier and Total Emissions

	tier 1 (% of total)	tier 2 (% of total)	tier 1 + 2 (% of total)
book publishers	5	1	6
power generation	92	1	93
average sector	14	12	26

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

where **x** is the vector (or list) of required inputs, **I** is the identity matrix (a table of all zeros except for the diagonal entries containing a 1), **A** is the direct requirements matrix (with rows representing the required inputs from other sectors to make a unit of output), and **y** is the vector of desired output. Terms in eq 1 represent the production of the desired output itself (**I*y**), contributions from the direct or first level suppliers (**A*y**), those from the second level indirect suppliers (**A*A*y**), and so on.

Once the supply chain is calculated, environmental emissions can be estimated by multiplying the output of each sector by its environmental impact per dollar of output:

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

where $\mathbf{b_i}$ is the vector of environmental burdens (such as GHG emissions for each production sector), and $\mathbf{R_i}$ is a matrix with diagonal elements representing the emissions per dollar of output for each sector.

With this economic input−output background, we can define the “tiers” for GHG protocols:

$$\text{Tier 1:} \quad \mathbf{b_i} = \mathbf{R_i}(\mathbf{I})\mathbf{y} = \mathbf{R_i y} \quad (3)$$

$$\text{Tier 2:} \quad \mathbf{b_i} = \mathbf{R_i}(\mathbf{I} + \mathbf{A'})\mathbf{y} \quad (4)$$

where **y** is a vector with output from the sector of interest and zero elsewhere, and **A′** is a truncated requirements matrix including only industry sectors providing energy inputs to the sector, such as power generation or steam. A full supply chain including indirect emissions (Tier 3 footprint) would result from applying eq 2.

As with any life-cycle calculation, this method has substantial uncertainties related to sectoral aggregation; price, temporal, and spatial variation; and several other issues, as discussed elsewhere (*8, 12*). Firm-level data such as electricity and energy use will produce more accurate footprint results, though allocation issues can confound even such specific data, as discussed in Ref. 6.

Results: Comparison of Tier 1, Tier 2, and Tier 3 Carbon Footprints

Using eqs 2, 3, and 4 for all 491 economic sectors in the U.S. economy, we find that the first 2 tiers as defined by most carbon footprint protocols include only a small fraction of the total supply chain (Tier 3) footprint for most industries. For the average sector, only 26% of the Tier 3 (total) GHG emissions are captured by Tiers 1 and 2 (Table 1). Nearly two-thirds of all economic sectors providing goods and services (323 of the 491 industries) would have less than 25% of their total carbon footprint represented by Tiers 1 and 2. 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). Sectors with large and known carbon footprints are already aware of their emissions (and more importantly, so are government agencies such as the U.S. EPA and the Department of Energy).

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, because a majority of their emissions occur farther down the supply chain than Tier 1 and Tier 2 examine. Further, these decision-makers may be lulled by existing protocols into assumptions that carbon legislation will mean little to them if they are not aware of the effect supply chain emissions will have on their input prices. Two case studies illustrate the differences between sectors.

Case Study 1: Book Publishers

Book publishers are a sector with 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 footprint represents only 6% of their total. Publishers also represent a sector where a large proportion of emissions would occur from final delivery, through either personal vehicle trips or package delivery services (*13, 14*). Although current standards would only include delivery emissions if trucks were owned by the publishers, consumers and some firms may wish (or be required) to take responsibility for these emissions.

Case Study 2: Power Generation

The U.S. power generation and supply sector is a well-known source of GHG emissions (contributing 37% annually (*15*)). Their own direct emissions from burning fossil fuels make up most of their footprint, with 92% of their total emissions in Tier 1. This is one of a handful of industries whose total Tier 3 footprint can be fairly accurately estimated with the Tier 1 boundary. Nevertheless, the delivery of fuels to power plants still represents a significant source of GHG emissions (such as rail deliveries of coal and natural gas pipelines). These emissions would probably fall outside of traditional Tier 1 and Tier 2 footprint approaches.

Discussion: Responsibility and Management with Carbon Footprints

Carbon footprints can be used for a variety of purposes, and surely the method used to calculate them should reflect these differing uses. The Tier 3 carbon footprint definition above is intended to aid effective management strategies. For instance, because firms can often influence their supply chains to some degree, a broad definition of carbon footprints can promote more effective corporate climate change policies. 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, because they would not be telling the whole story. Further, for both firms and consumers, life-cycle footprints show the maximum possible price increase in inputs/goods were a universal carbon price to be adopted.

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


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Calculation of a company's carbon footprint often accounts for direct emissions from the firm's operations and for the energy consumed, perhaps from a coal-burning power plant like the one here. But these are not the only factors in the total carbon footprint.

that 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. Lenzen (*16*) has developed a mathematically consistent and comprehensive way to assign total GHG emissions to, or share them among, different producers and consumers without double-counting.

However, just as there are problems with counting only Tiers 1 and 2, there are problems with responsibility sharing as well. Firms often 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 when using broad holistic approaches such as IO-LCA (*16*). Even if this issue could be overcome, it is unlikely many firms would spend the necessary time and money to calculate and, more importantly, understand 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 such reasons that the original protocols for carbon footprinting were written from a firm, instead of a product, perspective.

Further, double-counting is only a problem when participation in calculating footprints gets to a much higher degree than it already has or comprehensive regulation is imposed. And perhaps most importantly, *understanding the total life-cycle emissions associated with a firm's products will be helpful to the firm no matter how much of its Tier 3 emissions it wishes to take responsibility for*. This is because, as was argued during the negotiation of the Kyoto Protocol, flexibility and cost-effectiveness are extremely important to carbon mitigation efforts, and reducing supply chain carbon may be more cost-effective for firms than reducing direct or electricity-related emissions. In the future, with further voluntary or mandated participation, the type of corporate-oriented analysis suggested here might be used only for internal management purposes of goods and services, while allocation of carbon emission responsibilities could be developed for reporting or regulation.

In developing broad measures of carbon footprints, international trade should also be included. With growing international freight and greater production in countries with less stringent environmental regulations and higher carbon intensities, total carbon footprints should reflect the emissions due to transport and overseas production. The IO-LCA framework can be extended to estimate such international emissions (*17*).

Given the above discussion, we suggest a more comprehensive approach for footprint estimation. In addition to Tier 3 extension, an extended Tier 4 emissions calculation could be performed by adding in delivery, use, and disposal impacts of a product as a life-cycle product calculation. Thus, our suggested tiers are:

- Tier 1: No change: Emissions directly from company operations.
- Tier 2: No change: Emissions from energy inputs to company operations.
- Tier 3: Change to entire supply chain (cradle-to-gate) emissions for a good or service.
- Tier 4: Include total life-cycle emissions for production (Tier 3) plus delivery, use, and end-of-life.

Note that each of these tiers can be differentiated for geographically specific emissions. For corporations that assume end-of-life responsibility for their products (as in take-back programs), the disposal impacts would be included in the Tier 1 estimations. Again, the IO-LCA framework can be useful in estimating the end-of-life portion of the Tier 4 life-cycle emissions (*8, 18*), although specific process data will be necessary for the use phase.

At first, the calculation of Tiers 3 and 4 will be difficult for firms to complete, because internal data will not be sufficient to yield estimates of these emissions. An averaged screening-level analysis such as that presented here will be helpful for firms to understand emissions outside their own operations but within their supply chains. Such analysis is similar to hybrid life-cycle assessment (*8*). Eventually, as more companies report their own emissions, the averaged estimates for Tiers 3 and 4 can be replaced with firm-specific data that should be more accurate.

Conclusions

Many organizations are already pursuing carbon emission inventory projects to set a baseline for their carbon footprints in preparation for future carbon mitigation projects. Most of these groups look to the protocols for guidance in how to prepare their footprint inventories. However, our results suggest that these protocols will, in general, lead the organizations to footprint estimates that are relatively small in comparison with their total life-cycle footprints. Because the tools to estimate carbon footprints already exist within the life-cycle assessment community, we hope that firms will consider their life-cycle footprints from the outset, so that carbon mitigation efforts will be informed by the best available information, identify the true sources of emissions, and allow the largest sources of carbon emissions along the supply chain to be targeted first and most cost-effectively.

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