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Measuring Supply Chain Carbon Efficiency

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Introduction

The most recent Human Development Report for the United Nations Development Programme called climate change the “greatest challenge facing humanity” (UNDP 2007). Improving energy efficiency is a key issue for fighting climate change. In the near term improved efficiency and conservation are likely to have the greatest potential for reducing carbon emissions (Pacala and Socolow 2004). Recognizing that energy is consumed for the purposes of providing goods and services to the end consumer makes improving the efficiency of the supply chains that deliver those goods and services a key aspect of reducing carbon emissions (Carbon Trust 2006).

The focus on absolute emissions produced by individual companies has flaws that we address through measuring the carbon efficiency of the supply chain as a whole. This allows measurement of the relative impact of the goods produced by the supply chain. The environmental impact of products is typically measured through a process of Life-Cycle Assessment. In this paper we examine the issues with applying Life-Cycle Assessment to supply chains and develop a framework for measuring the supply chain carbon efficiency with product carbon labels.

Measuring Carbon Emissions

The most important agreement intended to fight climate change was the Kyoto Protocol, a 1997 international treaty that set limits on greenhouse gas emissions for certain countries. The Kyoto Protocol required certain industrialized countries to measure their greenhouse gas emissions and reduce them to a level 5% below their 1990 levels over time. The Intergovernmental Panel on Climate Change (IPCC) Guidelines provide a basis for developing greenhouse gas emissions

inventories (Oberthür and Ott 1999). The guidelines provide a list of emissions to be tracked as well as a conversion mechanism that can be used to provide a single standard measurement, carbon dioxide equivalents (CO₂e). The IPCC Guidelines provide for six categories of emissions generating activities that must be tracked: Energy; Industrial Processes; Solvents and Other Product Use; Agriculture; Land Use Change and Forestry; and Waste (IPCC 1996). Using these guidelines countries are able measure their emissions on an annual basis and work to meet their targeted emissions cuts.

Critics have pointed out numerous supposed flaws in the implementation of the Kyoto Protocol (Bohringer 2003). The Kyoto Protocol explicitly excludes emissions from international shipping, since technically they do not fall within a single national boundary (Peters and Hertwich 2008). Of greater significance is the issue of energy intensive processes shifting from countries with emissions targets to those with no controls. The effect of this is that emissions reductions in one country are offset by possibly greater increases in other countries. The percentage of reductions that are offset in this manner is referred to as the *carbon leakage*. Most estimates put the expected carbon leakage from Kyoto at 5-25%, but may actually be between 50-130% (Babiker 2005).

The effects of carbon leakage are due to the limited scope of the Kyoto Protocol, which exempts some countries from emissions targets. Even in countries without specific emissions targets the flaws of a national inventory system can give misleading impressions about environmental performance. Recent analysis of the carbon emissions embodied in imports and exports show that while the United States produces approximately 22% of the world's greenhouse gas

emissions the U.S. is responsible for 25-26% based on consumption (Weber and Matthews 2007). By drawing the system boundary at a national level the inventory procedures fail to account for the flow of goods in and out of the boundary, producing misleading results.

Corporate Emissions Inventories

The methods developed for measuring emissions in the Kyoto Protocol have been adopted by other organizations for use in measuring the greenhouse gas emissions of corporations. The GHG Protocol is an accounting framework developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). The Corporate Accounting and Reporting Standards provide guidance for setting organizational boundaries, identifying and calculating emissions, tracking emissions over time, and reporting emissions. Several programs, including the EPA Climate Leaders and the Chicago Climate Exchange, have adopted these standards for use in their programs (WBCSD and WRI, 2002).

The GHG Protocol places emissions into three scopes. Scope 1 emissions are defined to be those generated by direct combustion, either onsite or in company owned mobile sources. Scope 2 includes indirect emissions produced by the generation of purchased electricity. Scope 3 consists of other indirect emissions, including, but not limited to, those from employee travel, waste disposal, and production of purchased materials. The GHG Protocol is often used in programs that focus on emissions directly attributable to a company. For example, Scope 1 and Scope 2 are required in the EPA Climate Leaders program, and those emissions are referred to as the core emissions (EPA 2005).

This focus on the direct emissions of a company can create a carbon leakage effect in the supply chain.. Programs focused on reducing emissions only within the boundaries of one company can create incentives to shift emissions to other stages of the supply chain. A similar result has been shown in the case of supply chain inventory levels where optimizing at a single stage of the supply chain can result in a decrease in the performance of the supply chain as a whole (Lee and Billington 1992). True emissions reductions require improving emissions of the supply chain as a whole, creating the need for a method to measure supply chain carbon efficiency.

Measuring Carbon Efficiency

Numerous previous works have examined supply chain performance metrics, and Gunasekaran and Kobu provide a review of some recent literature on the subject (Gunasekaran and Kobu 2007). In their own review of the literature Lambert and Pohlen (Lambert and Pohlen 2001) note that performance measures that span the entire supply chain may not exist. One reason for this is that most companies focus on individual logistics measures rather than supply chain measures. This failure may be the result of not taking a systems approach, both internally within different functions of an organization and externally with many organizations operating as part of a single supply chain (Holmberg 2000).

A system level measurement can be provided through a performance management system that brings together individual performance metrics (Caplice and Sheffi 1995). Efficiency is one important individual metric that can be part of a total performance measurement system (Beamon 1999). Efficiency is usually measured as a ratio of outputs to inputs (Caplice and Sheffi 1994). The concept of efficiency is also used for a popular measure of sustainability, eco-efficiency, defined as the product or service value divided by the environmental impact

(Verfaillie, Bidwell et al. 2000). Such a measure can be used in developing an environmental performance indicator for supply chains (Michelsen, Fet et al. 2006).

The World Business Council for Sustainable Development (WBCSD) provides a set of generally applicable measures that can be used for all businesses to measure eco-efficiency (Verfaillie, Bidwell et al. 2000). If we limit the environmental impact to only the greenhouse gas emissions and measure the product value in terms of quantity of goods produced we create the following measure that we define as carbon efficiency:

$$\text{carbon efficiency} = \frac{\text{quantity of goods produced}}{\text{greenhouse gas emissions}}$$

The inverse of this measurement, the amount of greenhouse gas emissions per product unit, is commonly referred to as the carbon footprint of the product (Wiedmann and Minx 2008). Thus, the carbon footprint of a product is also a measure of the carbon efficiency of a supply chain. Reductions in the carbon footprint of a product represent an increase in the carbon efficiency of the supply chain.

The exact definition of what a supply chain is may differ between specific sources. In a review of the literature on supply chain definitions Mentzer et al (Mentzer, DeWitt et al. 2001) produce a definition of a supply chain as “a set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer.” They further extend this definition to include the idea of the *ultimate supply chain*, consisting of all the companies involved from the initial suppliers to the ultimate customer. The traditional supply chain definition and focus has been on the process of delivering products to the customer, but this can be extended to include a semi-closed loop

process that also includes the recycling, re-use, and remanufacturing of products and packaging (Beamon 1999). Other definitions of an extended supply chain include the traditional supply chain plus the use and disposal of the product (Christopher 1998). These extended definitions of supply chains allow us to include any emissions from initial suppliers to the ultimate consumer, the product use phase, and eventual disposal in the measurement of the carbon footprint. Measuring those emissions over the full life-cycle of a product can be accomplished through a method known as Life-Cycle Assessment.

Life-Cycle Assessment

Life-cycle Assessment (LCA) is a quantitative process for evaluating the total environmental impact of a product over its entire life-cycle, referred to as a cradle-to-grave approach. LCA is product focused, with emphasis on quantifying the environmental impacts (Heijungs 1996).

LCA, as defined by the International Standards Organization (ISO), consist of four phases:

1. Goal Definition and Scope
2. Inventory Analysis
3. Impact Assessment
4. Interpretation

In some instances only phases two and four need to be performed, in which case this is referred to as a Life-cycle Inventory (LCI) (International Standards Organization 2006).

The goal definition and scope phase includes identifying the product or function being studied, the reasons for carrying out the study, defining the system boundary, and identifying the data requirements. Inventory analysis involves identifying the process involved in the system, defining the inputs and outputs of each process, and collecting data to quantify those inputs and

outputs. Impact assessment defines impact categories and used the results of the inventory analysis to calculate indicator results in those categories. Finally, in the interpretation phase the results of the inventory analysis and impact assessment are interpreted in terms of the goal and scope definition; the results are checked for completeness, sensitivity, and consistency; and conclusions, limitations, and recommendations are reported (International Standards Organization 2006).

LCAs generally fall into two categories based on their purpose. An attributional LCA is focused on looking back on a product and determining what emissions can be attributed to it. A consequential LCA is focused on the environmental effects of what will happen due to a decrease or increase demands for goods and services (Ekvall and Weidema 2004). The types of LCAs are suitable for different purposes and require different types of data. An attributional LCA is appropriate for making specific environmental claims regarding a product, and typically makes use of average data for the product. The consequential category is more suited to performing scenario analysis. It often requires marginal data for the product as it requires making assumptions about economic factors related to changes in product consumption or production (Tillman 2000).

In addition to the types of LCA there are two main LCA methodologies: a process based approach and an Economic Input-Output (EIO) approach. In a process based methodology all phases of a product are examined and their inputs and outputs are mapped. This is typically considered the conventional method of LCA, and is sometimes referred to as the ISO or SETAC method (Lenzen 2001). The EIO-LCA approach uses broad economic categories to provide

environmental impacts, but generally only includes the production phase. The two methods can also be combined to form a hybrid approach (Facanha and Horvath, 2006).

Limitations of Life-cycle Assessment

While LCA provides a quantitative method well suited for measuring the carbon footprints of products it has limitations when applied to supply chains. We broadly classify these issues into two categories: methodological and informational. Methodological issues are differences in how the LCA is performed. While certain methodological choices may be appropriate for a particular study the differences in choices make comparison between LCAs difficult. Informational issues deal with the difficulty of acquiring accurate and detailed data needed to perform an LCA.

Life-cycle Assessment provides a general framework for measuring the environmental burden of a product or function. Its general structure allows application to a wide variety of items, but also allows considerable freedom in implementation. This freedom makes for difficulty in comparison between any two separate LCAs. Previous work has highlighted this lack of standardization in some important areas of Life-cycle Assessment, including defining system boundaries (Tillman, Ekvall et al. 1994; Suh, Lenzen et al. 2004) and allocation methods (Ekvall and Finnveden 2001; Ekvall and Weidema 2004). This lack of standardization means that while LCA provides a methodology for measuring a carbon footprint the results of two studies may not be comparable.

Process based LCAs have also been criticized for reasons related to their data requirements (Hendrickson, Horvath et al. 1997). The high cost and time of performing process based LCAs poses difficulties for products with complex supply chains spanning many organizations. In a

survey of LCA practitioners data collection was identified as the most time consuming and costly aspect of performing an LCA by the majority of respondents (Cooper and Fava 2006).

Collecting data across organizational boundaries presents issues with proprietary and confidential information, data accuracy, and a lack of representative data (Chevalier and Téo 1996; Huijbregts, Norris et al. 2001).

The second method of performing Life-cycle Assessments, referred to as Economic Input-Output LCA (EIO-LCA), provides an approach that requires less detailed process data. This work builds upon the original Economic Input-Output work of Wassily Leontief who developed the method for economic study. This method makes it possible to describe the output of one industry sector in terms of the inputs required from other sectors to produce that output. By assuming a linear proportionality any dollar value of output can then be expressed in the dollar values of inputs from other sectors required to produce it (Leontief 1986). The EIO-LCA model expands on this by adding the environmental burdens linked to industry sectors (Joshi 2000). Together this can be used to determine the total environmental burden of an industrial sector per dollar of sector output.

An EIO approach has several advantages over a process based LCA. By including all upstream activity within the economy the data is more complete, and there is no need to draw system boundaries. The data is generally compiled from publicly available sources, allowing for greater transparency than process based LCAs that use proprietary data. Finally, the EIO approach allows a much cheaper and faster method of providing results. In cases where only an

approximate result is needed an EIO LCA can provide a very rapid and inexpensive answer (Hendrickson, Horvarth et al. 1998).

The assumptions and methods of EIO analysis do have drawbacks for determining the environmental burdens of a specific product. Though EIO tables may contain hundreds of sectors this still requires significant aggregation of different products and processes. Some sectors may be too heterogeneous to produce correct results (Hendrickson, Horvarth et al. 1998). The information in the Input-Output tables only captures the effects of production, and therefore the use and disposal phases are not included (Joshi 2000). Many countries lack the sectoral environmental data needed for analysis, meaning that imports must be assumed to be homogeneous with domestic products (Suh and Huppes 2005). Finally, the nature of Input-Output analysis assumes proportionality between monetary and production flows (Lenzen 2001). That is, if a product doubles in cost then the environmental burden doubles as well. Though necessary for the computational results this may not reflect the reality of the production process.

In an attempt to build on the strengths of process based and EIO LCAs a third method has emerged, a hybrid of the two (Suh and Huppes 2005). The hybrid method uses a detailed processed based methodology for the important foreground processes, and an IO model to fill in the background processes (de Haes, Heijungs et al. 2004). The use of a hybrid method allows the IO method to be used to inexpensively provide complete data for the less important parts of the system, while using the more detailed and specific process data for the most important parts. In order to perform a hybrid LCA it is necessary to determine the boundaries between the IO and process-based systems. Poorly selecting these system boundaries can introduce significant error

(Suh and Huppes 2005). Hybrid LCAs may also involve some double counting, as portions of the process-based LCA may have been included in the IO data. However, this may still produce more accurate results than a pure process-based LCA which draws system boundaries and ignores processes which occur outside of the system (de Haes, Heijungs et al. 2004).

Each of the three methods discussed for performing an LCA present some issue for performing the measurement of a product carbon footprint. Process based LCAs lack standardization and require detailed data that can be difficult to obtain. EIO-LCAs aggregate information at sector levels and do not provide measurements specific to a supply chain. Hybrid LCAs, while they may provide better results in certain cases, suffer from a combination of the issues found in process based and EIO LCAs. This has led to the development of programs based on LCA designed specifically for carbon footprint measurement.

The Carbon Trust Carbon Label

The Carbon Trust is a U.K. based organization that has created the first standardized carbon label for placement on product packaging for sale. The label is intended to represent all emissions from production of raw materials through final disposal, but excluding in use emissions and emissions from in store activities. The emissions are to be measured per “Product Unit” where a Product Unit is a quantity that can be purchased by the customer. The methodology uses a process based LCA framework, referred to as a mass balance approach. After calculating these emissions the product label can be determined by summing the emissions across all sub processes and stages of the supply chain (Carbon Trust 2007).

Working from the initial Carbon Trust methodology the British Standards Institute (BSI) has developed a specification for measuring greenhouse gas emissions in products and services as a Publicly Available Standard known as PAS 2050 (British Standards Institute 2007). The standard provides guidelines on which emissions must be included in the calculations, recommendations for allocation procedures, the appropriate use of secondary sources, and drawing system boundaries.

This standard includes specific provisions for processes that are vague under current ISO standards (Weidema, Thrane et al. 2008). The BSI standard provides explicit guidance to exclude capital goods, use allocation instead of system expansion, and avoid recycling issues by drawing the system boundary at the point where a material becomes an input for a new product. The standard still leaves several areas open to interpretation that may reduce the ability to compare between products. While it does provide guidelines on certain minimum activities that must be included, such as emissions from factories and warehouses, it does allow flexibility in including other activities, such as emissions from office buildings. The standard also calls for the inclusion of the use and disposal phases of the product, but no guidance as to how those should be calculated. Further, it specifies that in use emissions should be reported separately, but without specifying how this should be communicated.

While the PAS 2050 specification provides a first step in solving the methodological issues of LCA it does not necessarily solve the informational problem. A company wishing to calculate the carbon footprint of its products still faces issues in acquiring accurate data upstream and downstream in the supply chain. Further, though PAS 2050 provides a standard for performing

the measurement it is not the only standard. The Japanese government recently announced its own version of a carbon label modeled loosely after the British standard (McCurry 2008). We propose the use of a carbon label as a framework for understanding how a carbon footprint can be measured in the context of a supply chain and how to characterize such a label.

A Framework for Carbon Labels

A label is a way to provide information about a specific product to consumers. This is necessary in the case of a product's carbon footprint where there is no way to identify this attribute from the product itself. In economic terms the carbon footprint of a product is a credence attribute—an attribute that can't be evaluated even after purchase and use (Darby and Karni 1973). This is in contrast to the other classes of attributes that can be identified either before or after use. A search attribute is one that consumers can evaluate prior to purchase, such as color, size, or weight. An experience attribute is one that can be evaluated only after purchase and use, such as the taste (Nelson 1970). The existence of credence attributes creates asymmetrical information between the consumer and producer. In his famous study of the market for used cars Akerlof examined how this asymmetry can create inefficiencies in the market (Akerlof 1970). One way producers can lessen the asymmetry is by providing useful information to the consumer through a label.

Carbon labels represent an opportunity for suppliers to provide information about the carbon footprint of their products to buyers downstream in the supply chain. This label would solve the information and aggregation problems currently associated with LCA by providing the relevant data that is specific to the particular supply chain. However, due to the nature of credence attributes such self reported labels are susceptible to “greenwashing” where companies claim

lower carbon footprints than reality. One way greenwashing can be reduced or prevented is through third party labeling services (Kirchhoff 2000).

The primary third party services used to increase confidence in labels are standards setting, testing, certification, and enforcement. A standard creates a common terminology for products that presents information in a uniform manner so that consumers may more easily understand the label and compare products. Certification provides an objective evaluation of the labeled attributes and provides credibility for the label claim. Enforcement increases the incentive for firms to provide truthful claims. Finally, testing can provide an objective measure of the claim (Golan, Kuchler et al. 2001). The Carbon Trust currently provides a third party standard and certification program for carbon labels. Self reported labels with additional third party services are common in the food industry as well, where nutrition labels are produced by the food manufacturers but subject to third party regulation by the FDA (Caswell and Padberg 1992).

While third party programs and regulations provide standards and certification; enforcement is often carried out through de-certification and legal methods (Golan, Kuchler et al. 2001). The role of testing for carbon labels is more complicated. In the case of credence attributes testing may not be possible, and instead an identity-preservation system is required to trace the attribute through the supply chain (Golan, Kuchler et al. 2001). The three characteristics of good traceability systems are: breadth, depth, and precision. Breadth refers to the information recorded by the system. Depth is how far backwards or forwards the system tracks. Precision is the degree of assurance the system can track a particular characteristic. In traceability systems the characteristics of the attribute determine the minimum breadth, depth, and precision required

to preserve a record of the attribute throughout the supply chain (Golan, Krissoff et al. 2004). Any carbon label can therefore be characterized in terms of these three dimensions.

Example – The Banana Case Study

In order to understand the effects that changes in these three dimensions can have on the carbon footprint measurement we partnered with two companies to study the carbon footprint of bananas. This study involved the cooperation of a leading international distributor of fruits and a regional grocery store chain. Working with the partner companies we examined the supply chain, identified sources of emissions, and gathered data necessary to calculate the carbon footprint. By considering the carbon footprint in terms of these dimensions we can understand how changes to each of these dimensions affect how the measurement is performed.

Description of the Supply Chain

Bananas sold in the United States are typically grown in Central America. Once they approach ripeness they are picked at the plantation and packaged for transportation. The bananas are shipped from the packing locations by truck in refrigerated containers to the outbound port. The bananas remain in the refrigerated containers and are loaded on ocean vessels for shipment to ports in the United States. From the inbound port the bananas are unloaded from the ship and sent by truck to distribution centers where they are chemically ripened and made ready for sale. From the DC they are sent by truck to stores where they are sold to the end consumer.

A number of additional materials are used to package the bananas for transport and sale. From the packing station to the DC bananas are normally shipped in container quantities. The bananas are packed in plastic liners, placed in cardboard boxes, and palletized for transport in the

containers. The packing materials are manufactured in the United States and delivered to the packing stations in the trucks that will be used to transport the bananas to the port. Additional packing materials include reusable wooden pallets, cardboard pieces used to help secure boxes of bananas on pallets, and plastic shrink wrap used when transporting pallets of bananas from the DC to the store. The banana boxes, plastic shrouds, and plastic shrink wrap are disposed of by the retailer, and in some cases are collected for recycling.

In addition to the bananas and packing materials a number of other materials are used in the banana supply chain. A variety of chemicals are applied at plantations to help grow the bananas, including fertilizers, pesticides, and fungicides. Ethylene fluid is used in specially designed banana rooms to chemically ripen the bananas before delivery to the retail outlet. Finally, at nearly every stage of the supply chain energy is required, either in the form of fuels such as diesel, oil, or natural gas; or through electricity and heat supplied by a utility provider.

The banana supply chain is fairly simple example. A fruit importer and grocery store chain typically control the banana from growth until purchase by the end consumer. A limited number of other suppliers provide chemicals, packing materials, transportation, and other services. Despite the simplicity of its supply chain the measurement of its carbon footprint is quite complicated. We can demonstrate this complexity by examining the supply chain using the three dimensions of breadth, depth, and precision needed to trace the claims made by a label.

Breadth

The first characteristic of the label is its breadth—what is included in the measurement. At the most basic level this covers which emissions should be included in the measurement. The term

carbon footprint has been used to include just carbon dioxide as well as for all greenhouse gas emissions expressed in carbon dioxide equivalents (Wiedmann and Minx 2008). A label must specify what emissions are included and what units they will be measured in.

Beyond the technical details like which types of emissions need to be measured the breadth determines which activities should be included. Corporate carbon measurement standards such as the GHG Protocol have placed the focus on whether emissions are emitted directly by the corporation or indirectly by other firms. This distinction is less relevant in the case of a supply chain. Emissions that are indirect for one firm are direct emissions for a different firm in the supply chain. Instead the focus is on which activities and materials fall within the scope of the product's supply chain. Clearly, emissions from activities and materials directly involved in the production and distribution of the product should be included; but inclusion of other activities such as employee commuting, business travel, and support functions is less clear.

The inclusion of capital goods and other goods that are not directly used in the product's supply chain represent another decision. Though clearly part of the system they have not always been included in LCAs, and their relevance to the system can vary by the type of product (Frischknecht, Althaus et al. 2007). Including capital goods adds an additional accounting issue to the measurement. Since these items have long lifetimes there is a need to allocate the emissions related to their production over the entire period of their use.

These decisions impact the banana carbon footprint in a number of ways. A number of gasses besides carbon dioxide are produced during the course of the banana's life cycle. Methane from

disposal at landfills and HFCs released during refrigeration can contribute to the carbon footprint if the breadth is expanded beyond simply carbon dioxide. Capital goods and infrastructure are required to transport, store, and ripen the bananas. This includes trucks, ocean vessels, ports, roads, buildings, refrigerated containers, pallets, forklifts, and a number of other items used throughout the supply chain. A number of other activities contribute indirectly to the production and sale of bananas. These can include energy use at office buildings, business travel, and production of advertising for the product. Inclusion of any of these activities expands the scope of the system boundary and presents questions on the appropriate method of allocating their emissions to the product.

The idea of breadth thus determines what is included in the measurement at any given stage of the supply chain. Activities, materials, and emissions that are within the breadth of the measurement are considered part of the supply chain and their life-cycle emissions should be included. This provides one dimension of the system boundary. The second dimension of the system boundary is the depth, which determines which stages of the life-cycle should be included.

Depth

The standard for LCA is a cradle-to-grave approach, where all inputs are traced back to their origin as raw materials and then followed until end of life. In practice such a standard is difficult to follow, and certain rules have been adopted to handle the high cost of tracing every material back to its raw material state. A number of cut-off rules have been identified in LCA studies, often based on quantities such as mass, economic value, or environmental relevance. These cut-off rules provide arbitrary standards for when tracing a material further up the supply chain can

be excluded. For example, a mass based cut-off rule might specify that if the mass of the material is less than 1% of the total product it does not need to be traced back to its raw state (Raynolds, Fraser et al. 2000). The use of different cut-off rules represents a methodological choice that prevents comparability between LCA studies and must be addressed in a carbon label.

Of special interest is the decision to include the supply chain for the production of energy sources. Calculators such as those made available by the GHG Protocol estimate the emissions from electricity generation and fuel combustion based solely on the emissions released during the fuel consumption. This ignores the other steps in the supply chain required to prepare fuel for use, such as extraction, refining, and transportation. LCA software applications normally take these considerations into account, such that burning a gallon of gasoline involves emissions not just from the carbon content of the gallon of fuel, but also from its production. This is the “well-to-wheel” scenario, as opposed to the “pump-to-wheel” analysis used by the GHG Protocol. Estimates of the efficiency of gasoline production are around 82%, meaning that 18% of the total energy is used up simply in producing the gasoline for combustion (Hekkert, Hendriks et al. 2005).

Depth plays an important role not just in determining how far back in the supply chain products should be traced, but how far forward as well. Tracing life-cycle impacts forward in the supply chain is a difficult problem because at some point the product typically passes into the hands of an end consumer. At this point differences in how consumers use and dispose of the product affect the life-cycle impacts. Deciding whether to include these impacts and how to account for

them is a difficult challenge. For products that consume energy in the use phase this is an especially important decision, as the impact of the use phase of those products can dominate the production and disposal phases.

The banana is a simple product—once purchased by the consumer it is typically consumed without any additional refrigeration or processing such as cooking. Despite this simplicity there are still several actions that could add to the life-cycle emissions of the product. The banana is typically purchased at the store and transported home, which could involve emissions from travel. Consumers may place the bananas in paper or plastic bags to carry home from the store. In some cases the bananas may be used as ingredients in a dish that requires energy for cooking. The peel of the banana is likely to be disposed of, and this may produce emissions from composting or decay at the landfill. Including any of these activities requires making assumptions about a number of scenarios that may occur, and what the impact of those scenarios will be.

Changes in the depth of the standard can have clear affects on the measured carbon footprint, but it also creates challenges in information collection and calculation. Including stages that are impacted by the decisions of different consumers requires methods of estimating those emissions. For products with in use emissions or recyclable materials these decisions on how to perform the estimation can have significant impacts on the final results, and so far the LCA community has not developed a single standard method of accounting for these impacts.

Precision

The final dimension that defines a standard is the precision at which the measurement is performed. This includes determining when to draw a distinction between two products of the same supply chain and the appropriate use of secondary data. Two products produced by the same supply chain may vary in a number of factors such as the distance shipped to final destination, the source of components, and the manufacturing location. Further, the carbon footprint of a product represents a snapshot of the supply chain at a certain point in time. How long that snapshot is valid and over what period of time data can be averaged contribute to the precision of the label.

The determination of appropriate secondary data sources is an important one given the difficulty in directly monitoring emissions. When direct emissions monitoring is not available measurable data such as kWh of electricity and gallons of diesel fuel consumed must be converted into carbon emissions through the use of emissions factors. The choice of factors affects the precision of the carbon footprint. For example, emissions factors per kWh of electricity are available through the EPA at the level of specific power plants, averaged by energy provider, averages produced in specific states, and at the average national level. These factors can produce significantly different results considering that the state level emissions factor for Vermont was only 6 lbs/MWh compared with 2386 lbs/MWh for the state of North Dakota (EPA 2007). Any standard must specify what the appropriate sources of secondary information are, and how they can be used.

Though each banana follows similar steps in the supply chain, the actual path can be quite different. Bananas imported by a single company may be grown at hundreds of different farms, each of which may use different amounts of chemicals in the growing process. Even within the same farm different amounts of chemicals may be used during different time periods due to changes in growing conditions. Different bananas may have different travel distances to the outbound port, during the ocean voyage, from the inbound port to a DC, to the retail outlet, to the consumer, and finally to the place of final disposal. DCs and stores consume different amounts of electricity that is provided by different generation methods. Some shipments make better utilization of the truck or vessel. The precision of the carbon label must determine which of these factors are relevant for making a distinction between two products and which differences can be averaged into a single number.

Conclusion

Current schemes for measuring carbon emissions have focused on measurements within national or corporate boundaries. Such schemes are prone to problems with carbon leakage, a process whereby emissions reductions that occur within the system boundary are offset by increases outside the boundary. For companies the focus on reducing emissions within their corporate boundaries can lead to inefficient strategies by ignoring opportunities to reduce emissions elsewhere in their supply chain. This requires a method of measuring carbon efficiency for the entire supply chain, and we propose the carbon footprint of a product as this measure.

The typical method of quantifying the environmental impact of a product is through Life-cycle Assessment. This method is theoretically well suited to measuring a product's carbon footprint, but is difficult to implement in practice. We identify two types of problems with LCA—

methodological and informational. Methodological problems arise from different choices in system boundaries, allocation methods, and handling of end of life issues. These differences make comparisons between the results of different LCA studies difficult. Informational problems are caused by the difficulty in acquiring data that is cost effective and accurate for the product being studied. Current approaches provide solutions that solve the cost effectiveness issue but are not specific to a particular supply chain.

We develop a framework for measuring the carbon footprint using the idea of a carbon label. A label solves the informational issue by allowing communication of claims about the product attributes between firms in the supply chain. Due to the nature of carbon footprints such claims are likely to be considered untrustworthy, but third party services such as standards setting and certification can improve the confidence in these labels. The three dimensions of breadth, depth, and precision define the necessary attributes of the measurement needed for a carbon label. In the future this framework may be used to develop and evaluate standards for carbon footprint measurement. Such standards would allow effective communication between supply chain partners and create the opportunity for benchmarking supply chain carbon efficiency.

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