Measuring Supply Chain Carbon Efficiency: A Carbon Label Framework

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Abstract

In the near term, efficiency improvements represent a key option for reducing the impacts of climate change. The growing awareness of climate change has increased the attention regarding the carbon emissions "embedded" in the products we consume. This increased attention creates a need to measure and improve the carbon efficiency of the supply chains that produce those goods. In this thesis we present a method for measuring the carbon efficiency of a supply chain that recognizes the decentralized nature of supply chains.

First, drawing from concepts in supply chain performance measurement and eco-efficiency we propose a definition of supply chain carbon efficiency that is consistent with the idea of a product's carbon footprint. We present Life Cycle Assessment (LCA), a method for quantifying the environmental impact of a product or service, as the appropriate method of measuring a product's carbon footprint and demonstrate the use of LCA through a case study involving the supply chain of bananas.

Next, we characterize the difficulty and uncertainty in performing an LCA of a supply chain through an analysis of our case study of bananas. We present a framework to reduce the uncertainty though the concept of a carbon label. The carbon label provides a system where firms can measure the carbon footprint of their activities and share this information with their supply chain partners. We identify the role of third parties in facilitating information sharing and define the characteristics that describe the carbon label.

Finally, we demonstrate how the carbon label works in the context of the supply chain. Through an analysis of the mode and carrier assignment steps in an integrated supply chain we develop new metrics that show how sharing information can increase the accuracy of the measured carbon footprint and improve decision-making. We provide incentive for firms to share information through the development of a vertical differentiation model of product carbon labels. Our model shows how consumer demand for lower carbon products drives reductions in the carbon footprint throughout the supply chain and induces firms to voluntarily disclose their carbon footprint.

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Last, and certainly not least, I'd like to thank Emily Sheldon for her help, encouragement, and support over the years. From telling me where to put the commas to dealing with my occasional frustration, you've always been there when I needed you.

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List of Abbreviations

ABC	Activity Based Costing
B	Boron
B2B	Business-to-business
B2C	Business-to-consumer
BSI	British Standards Institute
BTU	British Thermal Unit
CaO	Calcium oxide
CBI	Chiquita Brands International
CCX	Chicago Climate Exchange
CH4	Methane
CNG	Compressed Natural Gas
CO2	Carbon dioxide
CO2e	Carbon Dioxide Equivalent
CSR	Corporate Social Responsibility
Cu	Copper
DC	Distribution Center
Defra	United Kingdom Department for Environment, Food, and Rural Affairs
EIA	United States Energy Information Administration
EIO	Economic Input-Output
EPA	United States Environmental Protection Agency
EU	European Union

EU ETS	European Union Emissions Trading Scheme
Fe	Iron
FHWA	Federal Highway Administration
GDP	Gross Domestic Product
gge	Gallons of Gasoline Equivalent
GHG	Greenhouse Gas
GRI	Global Reporting Initiative
GWP	Global Warming Potential
ha	Hectare
HDPE	High-density polyethylene plastic
HHV	Higher Heating Value
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRU	International Road Transport Union
ISO	International Organization for Standardization
K2O	Potassium oxide
kWh	Kilowatt-hour
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LDPE	Low-density polyethylene plastic
LTL	Less-than-truckload
MgO	Magnesium oxide
Mn	Manganese
MPG	Miles per gallon
mph	Miles per hour
MWth	Megawatt thermal
N	Nitrogen

N2O	Nitrous Oxide
NTM	Network for Transport and Environment
OECD	Organisation for Economic Co-operation and Development
P2O5	Phosphorus pentoxide
PAS	Publicly Available Specification
PCR	Product category rule
S	Sulfur
SCM	Supply Chain Management
SETAC	Society of Environmental Toxicology and Chemistry
tkm	tonne-kilometer
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
WBCSD	World Business Council for Sustainable Development
WRI	World Resources Institute
Zn	Zinc

Chapter 1

Introduction

The 2007/2008 Human Development Report for the United Nations Development Programme (UNDP) called climate change the "greatest challenge facing humanity" (UNDP, 2007). Improving efficiency is a key issue for fighting climate change, as in the near term improved efficiency and conservation are likely to have the greatest potential for reducing carbon emissions (Pacala and Socolow, 2004). Much of the current focus on reducing carbon emissions has been focused on the producers of emissions. However, the most recent UNDP Human Development Report (UNDP, 2011) highlighted that "runaway growth in consumption among the best-off people in the world is placing unprecedented pressure on the environment." The Carbon Trust, a U.K. organization dedicated to accelerating the move to a low carbon economy, has stated that consumer purchasing decisions are the ultimate driver of carbon emissions, and that all emissions can be attributed to delivery of products and services to those consumers (Carbon Trust, 2006). This makes improving the carbon efficiency of the supply chains that produce those goods and services a key aspect of reducing the impact of climate change.

1.1 Current Mitigation Efforts

Current policies for fighting climate change have focused on producers of emissions. This includes national level policies such as the Kyoto Protocol, as well as corporate level initiatives such as the Carbon Disclosure Project (CDP). This focus has resulted in standards of measuring carbon emissions that are based on national or corporate boundaries and absolute levels of emissions rather than efficiency. Understanding these current approaches provides help in seeing the role of supply chain carbon efficiency measures.

1.1.1 National Emissions Inventories and the Kyoto Protocol

The most important agreement intended to fight climate change was the Kyoto Protocol, a 1997 international treaty that set limits on greenhouse gas (GHG) emissions for certain countries. The Kyoto Protocol required certain industrialized countries to measure their GHG emissions and reduce them to a level 5% below their 1990 levels over time (Oberthur and Ott, 1999). The Intergovernmental Panel on Climate Change (IPCC) Guidelines (2006) provide a basis for developing an accounting of all greenhouse gases emitted to or removed from the atmosphere over a given time, referred to as a GHG inventory. The Kyoto Protocol covers the six main greenhouse gases, sometimes referred to as the Kyoto gases: carbon dioxide (CO_2); methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). The guidelines provide a conversion mechanism that can be used to provide a single standard measurement for how much warming would be caused by a given amount and type of greenhouse gas. The standard measurement is in terms of carbon dioxide equivalents (CO_2e), representing the equivalent mass of CO_2 needed to produce the same global warming effect. The conversion mechanism is based on global warming potential (GWP) figures developed by the IPCC that specify the amount of warming caused by the gas relative to CO_2. As these gases remain in the atmosphere for different lengths of time, they may produce a different amount of warming over various time horizons. The IPCC specifies GWP factors for 20, 100, and 500 year time horizons. 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. Using these guidelines, countries would measure their emissions on an annual basis and work to meet their targeted emissions cuts.

The Kyoto Protocol provided several flexible mechanisms to help countries meet their obligations, including the ability to develop emissions trading programs. Under an emissions trading scheme a member would be allowed to allocate a number of carbon permits, each representing the right to emit one metric tonne of CO_2e, equal to their allowed carbon emissions. The allowances thus set a cap on the total amount of emissions allowed by all participants in the trading scheme. By making the permits tradable, one member could emit more than the allowed quota of emissions by purchasing additional permits from members that are below the allowable limit. In this way emissions can be reduced in a more efficient manner, as members who find it expensive to reduce emissions can purchase the excess permits from members who are more efficiently able to meet their targets (Oberthur and Ott, 1999).

The trading program approach was one chosen for use by the European Union (EU). Under the European Union Emissions Trading Scheme (EU ETS) each country was allowed to allocate a certain number of permits. Each individual nation was then able to allocate the permits to individual installations that produce the emissions, and those installations would participate in the trading market. The focus in the scheme was on the large power producers, and any installation producing more than twenty megawatts of thermal power was to be included in the scheme (Ellerman, Buchner, and Carraro, 2007). This approach created a method for countries to monitor and reduce the carbon emissions produced in their borders while letting installations make decisions best suited for their situation.

While the Kyoto Protocol is not without its flaws, it has influenced the development of further emissions reduction programs. Kyoto took what was a global problem of emissions reduction and created a system where individual countries were given targets for their own emissions reduction. The implementation of the EU ETS took this a step farther and changed the problem from the level of a national emissions reduction to one focused on individual installations. This general structure has been adopted and spread to a number of other programs designed to work at the corporate level. These programs include voluntary carbon exchanges that work similar to the EU ETS, such as the Chicago Climate Exchange (CCX), as well as corporate emissions reduction efforts related to sponsored programs or internal Corporate Social Responsibility (CSR) programs (Bayon, Hawn, and Hamilton, 2007). These corporate programs require their own guidelines for developing emissions inventories similar to those developed by the IPCC for national inventories.

1.1.2 Corporate Emissions Inventories

The GHG Protocol Corporate Accounting and Reporting Standards (WRI and WBCSD, 2004) is an accounting framework developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). Its website describes it as "the most widely used international accounting tool for government and business leaders to understand, quantify, and manage greenhouse gas emissions" (Greenhouse Gas Protocol, 2011). The purpose of the framework is to provide a set of standards for corporations and government entities to inventory and report their greenhouse gas emissions. The structure and measurements are based on the guidelines established by the IPCC. The standards provide guidance for setting organizational boundaries, identifying and calculating emissions, tracking emissions over time, and reporting emissions. Several programs have adopted the GHG Protocol standards to require tracking at the corporate level, including the U.S. Environmental Protection Agency's (EPA) Climate Leaders and the CCX. The protocol places emissions in three different scopes, but does not provide guidance on which scopes should be included in a specific program, instead leaving that decision up to the actual program implementation. The different scopes defined in the GHG Protocol are shown in Figure 1-1.

Scope 1 emissions are defined as direct emissions from sources owned or controlled by the company. This includes direct combustion of fuels to generate electricity, steam, or heat in stationary sources; physical or chemical processes that release emissions; combustion of fuels in company owned mobile sources for transportation; and direct release of gases such as refrigerant leaks or methane venting. 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.

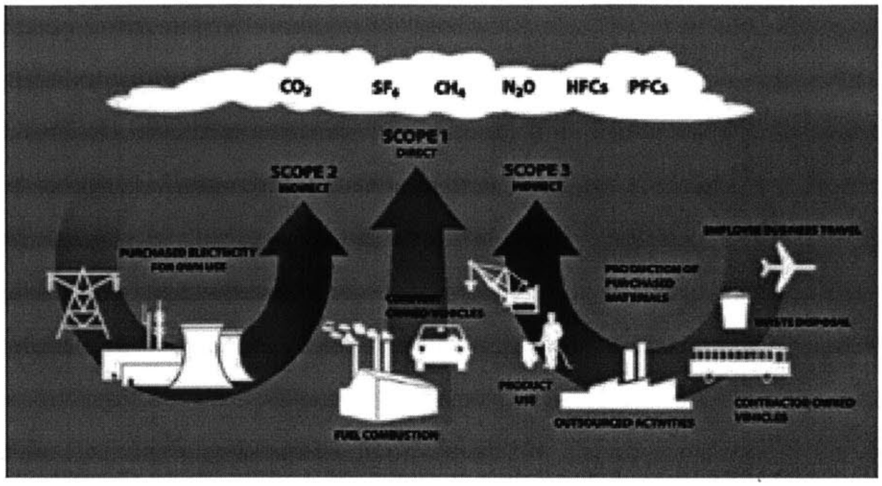


Figure 1-1: GHG Protocol Emissions Scopes (WRI and WBCSD, 2004)

1.2 Measuring Corporate Carbon Footprints: RetailCo Case Study

In this section we provide an example of measuring a corporate carbon footprint through a case study done in conjunction with RetailCo[1], a national retail chain. This study was the first attempt by RetailCo to measure the carbon footprint of the corporation as a whole, using the year 2007 as a baseline. The following section details the work we performed to develop the carbon footprint boundary, collect the data, and the results of our analysis.

1.2.1 Carbon Footprint Boundary

Based on discussions with RetailCo, the boundary we set for the carbon footprint calculation is shown in Figure 1-2. This boundary includes:

- Electricity and natural gas usage at RetailCo facilities, including stores, offices, and distribution centers (DCs).
- Product shuttle deliveries between DCs and DC to store deliveries controlled by RetailCo, whether performed by the RetailCo private fleet or dedicated third party carriers.

[1]The name has been changed to protect proprietary data

- Emissions from employee travel in RetailCo vehicles, including the corporate car fleet and corporate jets.
- Emissions from employee business travel due to air travel and rental car usage.

Sources of emissions that were included in the system boundary, but for which data was not available were:

- Waste disposal at RetailCo facilities.
- Fugitive emissions from refrigerants at RetailCo facilities.

Together these emissions consist of all scope 1 and scope 2 emissions, as well as some scope 3 emissions. Sources of emissions that were excluded from the boundary include:

- Emissions related to the production of goods purchased and sold by RetailCo.
- Delivery of products to DCs or stores performed directly by suppliers.
- Employee commuting.
- Consumer transportation to and from RetailCo stores.
- Consumer use and disposal of products sold by RetailCo.
- Direct delivery of products to consumers, such as through online ordering, performed by third party carriers.

The year 2007 was chosen as the base year for the analysis, and all information was collected for that calendar year.

1.2.2 Methodology and Data Sources

The calculations for this analysis were done in accordance with the specifications of the GHG Protocol published by the WRI/WBCSD. A number of tools were employed in this analysis. Emissions from purchased electricity were calculated using the tool for "Indirect CO_2 Emissions from Purchased Electricity" (WRI, 2007b). This tool requires data regarding

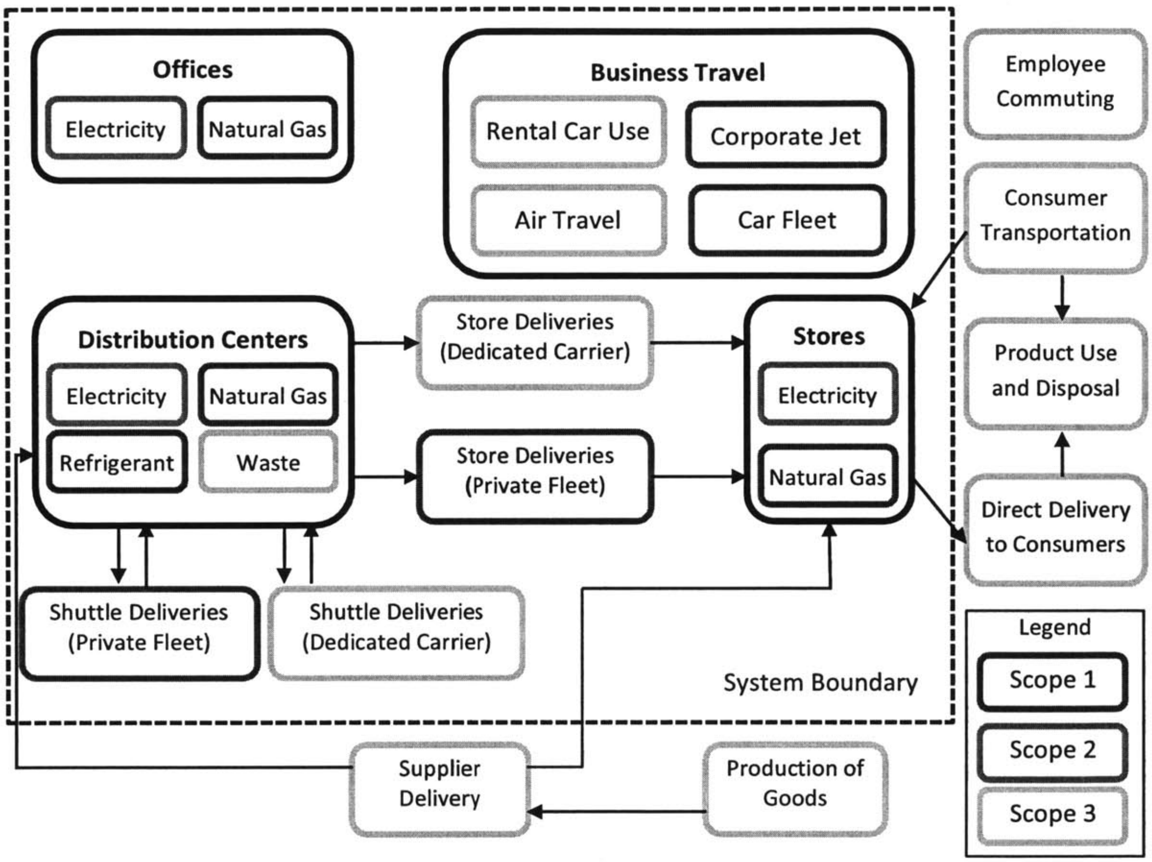


Figure 1-2: RetailCo Corporate Boundary

the amount of electricity used in kilowatt-hours (kWh) and the location where the electricity was purchased. The location is used to determine which emissions factor, in terms of CO_2 per kWh, is appropriate based on the US sub-region where the electricity is purchased. Different areas of the US produce electricity using different fuel mixes, which means that electricity produced in certain areas may have higher or lower carbon emissions than average. The use of regional emissions factors is intended to capture this difference in fuel mix.

Data for electricity consumption was obtained through an online system that keeps track of utility usage at RetailCo facilities. Facilities were separated into three categories—stores, offices, and distribution centers—based on a site numbering system used by RetailCo. The system included records for 6,788 accounts that consumed electricity in 2007. This was comprised of 32 office locations, 29 distribution centers, and 6,727 stores. Approximately 400 sites did not have complete location records, and have not been matched with the appropriate US sub-region. For this reason the initial analysis used the national average carbon emissions factor for all locations.

Some RetailCo facilities still have utilities paid by a landlord. For these facilities the average annual payment to the landlord for electricity was calculated from billing data provided by RetailCo. Electricity consumption for these stores was estimated using the total payments divided by the average cost paid per kWh for facilities where RetailCo managed the utilities.

Natural gas consumption at each facility was obtained through the online system as well. The records indicated 4,725 sites consumed natural gas in 2007. This represents 24 distribution centers, 19 office buildings, and 4,682 stores. Usage was reported in therms, equivalent to 100,000 british thermal units (BTU). To calculate carbon emissions the tool "GHG Emissions from Fuel Use in Facilities" (WRI, 2007a) was used. The total usage was converted from therms to terajoules and the default GHG factor for the Higher Heating Value (HHV) of natural gas was applied to determine the emissions.

Emissions from DC and store deliveries made by RetailCo and their dedicated carriers were calculated using the tool "Mobile Combustion CO_2 Emissions Calculation Tool" (WRI, 2003). Data for store deliveries was provided by RetailCo and consisted of the total fuel use and miles driven for all deliveries in 2007. This was further broken down between private and dedicated carriers as well as store and shuttle deliveries. Deliveries by the RetailCo private fleet and dedicated third party carriers were assumed to use diesel fuel, and emissions were calculated using the fuel-based methodology. This method specifies capturing the actual fuel consumed and calculating the carbon emissions based on the carbon content of the fuel. This method is preferred over the other possible methodology, which is distanced-based.

Emissions from RetailCo corporate jets and the RetailCo car fleet were calculated using fuel-based methodologies specified in the GHG Protocol calculator "CO_2 Emissions from Business Travel" (WRI, 2006). Data regarding fuel usage in the RetailCo car fleet was provided and consisted of the number of gallons of each type of fuel purchased by employees. This data was obtained from purchase records using company gas cards. Data for RetailCo jet use consisted of total fuel purchases and mileages. Emissions were calculated using the total fuel consumed by type and the appropriate emissions factor for that type of fuel. The calculator provides two options for flight travel, jet kerosene and aviation gasoline. The fuel used by RetailCo planes was assumed to be jet kerosene, as this is the primary fuel type for executive jets and commercial aircraft (EPA, 2008a). Jet kerosene contains about 15% more carbon than aviation gasoline, so this represents an upper bound on the amount of carbon emissions from the RetailCo air fleet.

For the RetailCo car fleet the standard gasoline carbon factor was applied for purchases of regular, mid-grade, and premium fuel. The standard diesel carbon factor was used for purchases identified as diesel. Approximately 1,570 gallons of Compressed Natural Gas (CNG), 928 gallons of E85 ethanol, and 29,613 gallons of "other" were used. The GHG Protocol does not specify an exact emissions factor for CNG. Instead emissions were calculated by converting from the number of gge (gallons of gas equivalent) of CNG purchased to the total number of therms those gges represent, and then calculating emissions based on the amount of carbon per therm. No factor currently exists for E85, and emissions were calculated using the normal gasoline emissions factor. This likely represents an overestimation of the emissions, but due to the small amount of E85 used the error is very small relative to the overall amount of carbon. For those purchases listed as "other" the standard gasoline emissions factor was used.

Emissions for employee rental car use were calculated using a distanced-based methodology. This uses the actual distance traveled and then determines the approximate fuel usage based on the average fuel efficiency of the vehicle. This method is considered less precise than fuel-based methods, as it does not account for variables such as city vs. highway driving or the driving behavior of the vehicle operator. Data for this calculation was provided to RetailCo by the rental car companies and consisted of the total miles driven and average fuel economy of each different vehicle class offered by the companies. The distance and fuel economy were used to estimate the amount of fuel consumed, and carbon emissions were then calculated based on the carbon content of the fuel.

Emissions from air travel were computed using the distance-based methodology from the tool "CO_2 Emissions from Business Travel" (WRI, 2006). The tool specifies an emissions factor in kg of CO_2 per mile of air travel for flights of three different lengths: short (<500 km), medium (between 500 and 1600 km), and long (>1600 km). Using travel records provided by RetailCo, the number of flights of each length were provided for 2007. For each flight the distance was calculated and the appropriate emissions factor applied to determine the total carbon emissions.

Emissions from waste disposal and refrigerants were intended to be included in this analysis, but were omitted due to a lack of data. Emissions from refrigerants are calculated based on the amount of each type of refrigerant that escapes into the atmosphere during initial filling, regular maintenance fillings, and end of life service for cooling equipment. In situations where no new equipment is installed or old equipment removed, the amount of refrigerant released into the atmosphere can be measured by the total amount added to the equipment to top off the tanks during the year. This needs to be done for each piece of equipment. Since different equipment may use different types of refrigerant, the specific refrigerant used must be recorded so that the appropriate emissions factor can be applied.

Currently RetailCo has supplied a list of the number of pieces of cooling equipment installed at DCs, the type of refrigerant used in the equipment, and the total cooling tonnage of the equipment. Though this information is not detailed enough to calculate the actual emissions it does provide useful information regarding the current refrigerants used at RetailCo facilities. About 75% of total cooling tonnage uses R22 as the refrigerant. R22 is an ozone depleting substance that is being phased out as part of the Montreal Protocol. As

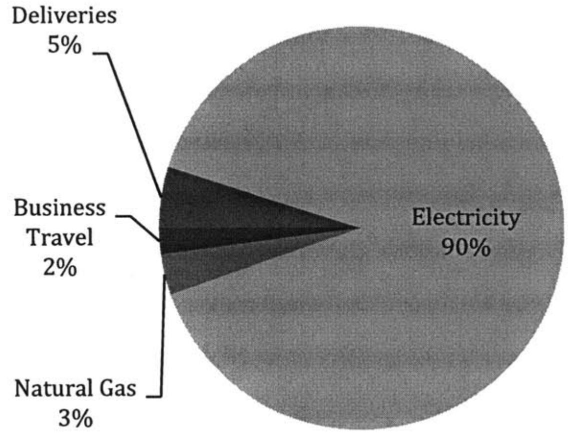


Figure 1-3: Share of RetailCo Emissions by Source

such it is not covered under the Kyoto Protocol and is not reported for the GHG Protocol. It does have global warming potential, however, and RetailCo may wish to report this information. The only other refrigerant used in this equipment was R134A, a substance that is included in the GHG Protocol. Based on an initial screening analysis recommended by the GHG Protocol, RetailCo should seek to gather data from refrigerant usage for inclusion in the corporate footprint, as at the upper bound of equipment leakage rates total emissions would meet the threshold for significance.

1.2.3 Results

Based on the defined boundary and the data collected, the initial carbon footprint calculation for RetailCo in the year 2007 was approximately 1.51 million metric tonnes of CO_2e. The vast majority of this is produced by the consumption of electricity in RetailCo facilities, accounting for nearly 90% of the total emissions. The remaining emissions are due to diesel consumption used for product deliveries (5%), natural gas usage in facilities (3%), and business travel (2%). This is summarized in Figure 1-3. These emissions can be broken down between stores, DCs, and offices as shown in Table 1.1.

Location	Metric Tonnes CO_2e
Stores	1,263,988
DCs	70,717
Offices	19,733

Table 1.1: Emissions by Location Type

1.3 Problems with National and Corporate Emissions Inventories

One significant problem for emissions inventories with limited boundaries is energy intensive processes shifting from within the boundary to outside. For national level programs such as the Kyoto Protocol, the effect 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. Analysis of the carbon emissions embodied in imports and exports shows 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.

A similar carbon leakage problem exists for corporate level inventories, where emissions can be moved outside a corporate boundary by shifting them up or down the supply chain. This view of emissions as being separated by corporate boundaries is shown below in Figure 1-4. In this view, five companies together comprise a supply chain that flows from upstream at the extraction of raw materials to downstream at delivery of a finished good to the consumer. Each step in the supply chain is owned by a different firm and produces some GHG emissions. Under a corporate view of emissions each company draws a boundary around their portion

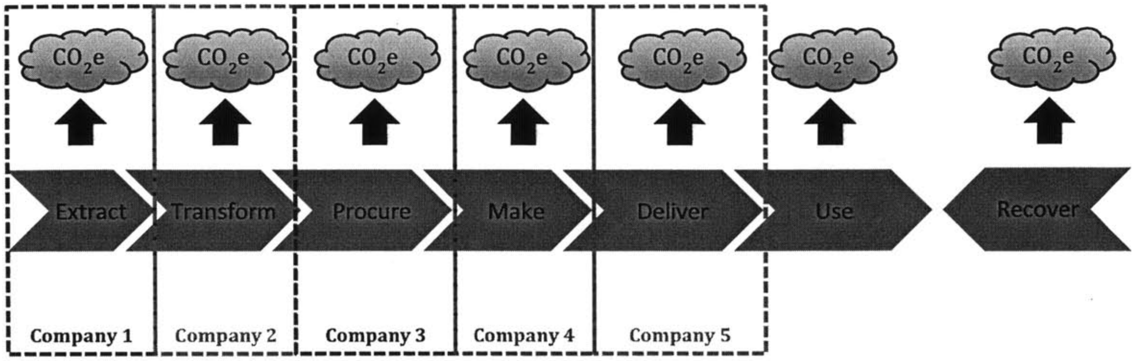


Figure 1-4: Corporate View of Emissions

of the supply chain and accounts for emissions within this boundary. Each firm has incentive to reduce emissions by shifting activities upstream or downstream in the supply chain. Since the use and disposal of the product fall outside the ownership of the firms in the supply chain, none of them have incentive to account for and reduce those emissions, ignoring a potentially significant share of total emissions.

Further, this view makes comparisons between firms difficult, as firms operating in the same industry may control different portions of their supply chain. In a competitive benchmarking process a company compares their performance with that of major competitors to determine what it takes to improve (Bagchi, 1996), but these comparisons are often difficult due to the limited amount of information available and differences in calculation methodologies. Several other retailers do provide information regarding their carbon footprint that can be compared to RetailCo. This data is based on information publicly available from company websites or other publications. This comparison is shown in Table 1.2.

On the basis of CO_2e per square foot, RetailCo compares favorably to other retailers such as Tesco, Marks & Spencer, and Wal-Mart. The reported number is higher than that of Target stores, but limited details published by Target make a comparison difficult. Given the high level of emissions from electricity for RetailCo, the percentage of emissions from electricity consumption is a key point of concern. The 90% figure for RetailCo is high compared to Tesco and Wal-Mart, but not when compared to Limited Brands and Marks & Spencer. It is unclear whether this is due to performance by RetailCo, differences in cal-

Retailer	CO_2e (metric tonnes)	Stores	CO_2e per Store	Sq. Ft.	CO_2e per sq. ft	Year	% Electricity
RetailCo	1,510,000	6,200	243.55	71,348,850	0.02	2007	90%
Tesco	4,130,000	3,262	1,266.09	68,100,000	0.06	2007	57%
Wal-Mart	20,388,574	7,022	2,903.53	1,313,114,000	0.02	2006	72%
REI	103,000	80	1,287.50				23%
Target	2,630,000	1,488	1,767.47	192,064,000	0.01	2006	"vast majority"
Marks & Spencer	515,000	500	1,030.00	12,500,000	0.04	2007	84%
Limited Brands	886,658	2,900	305.74			2006	98%

Table 1.2: Comparison of RetailCo to Other Retailers

culation methodologies, or differences in supply chain ownership. For example, refrigerants accounted for 17% of the total for Tesco but were not included in the carbon footprint of RetailCo. The variation in performance may be due to differences in activities within the supply chain that each firm controls. Clift and Wright (2000) showed that industries in the U.K. generally associated with the upstream portion of the supply chain tend to be higher in emissions per dollar. Thus, it is difficult to identify whether one firm is more efficient than another when they control different aspects of their supply chain. REI includes emissions from its REI Adventures travel company, explaining the low percentage of total emissions from electricity. Wal-Mart operates one of the largest private truck fleets in the country, contributing to their non-electricity emissions. The lack of a consistent basis to compare between firms makes judging overall performance difficult.

This corporate view of carbon emissions also creates incentive to optimize at only one stage of the supply chain, a result that can actually decrease the performance of the supply chain as a whole (Lee and Billington, 1992). Matthews, Hendrickson, and Weber (2008) estimated that scope 1 and scope 2 emissions account for only 26% of total supply chain emissions on average. The focus on the more easily measured scope 1 and scope 2 emissions ignores potentially important indirect effects of changes that may occur upstream or downstream in the supply chain (Weber, Koomey, and Matthews, 2010). For example, RetailCo could reduce their total carbon footprint by shifting more store deliveries to direct supplier deliveries, moving those emissions from scope 1 to scope 3 and outside their system boundary. However, it is unclear whether this would result in an actual reduction in the carbon footprint of the supply chain, as the direct store deliveries could be less efficient than the

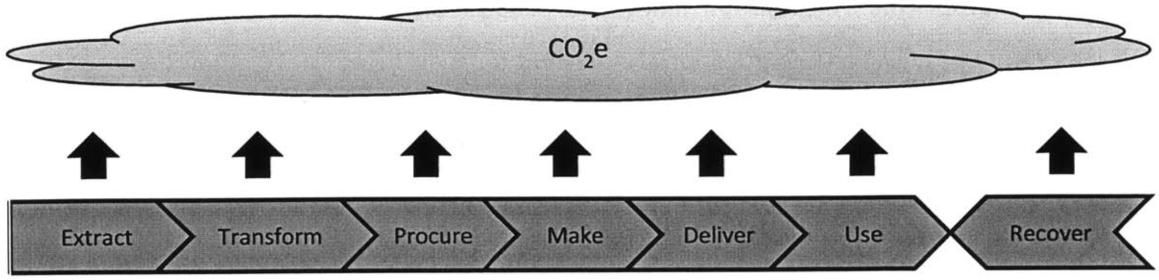


Figure 1-5: Supply Chain View of Emissions

current system. Thus, a corporate view encourages a narrow view of emissions in comparison to the supply chain as a whole.

The problems with boundaries and efficient emissions reduction strategies can be improved by instead taking a supply chain view of carbon emissions, as shown in Figure 1-5. The common boundary allows for effective benchmarking by comparing performance between supply chains and the products they produce rather than individual companies. In this case the total carbon emissions for all stages of the supply chain are measured; therefore no incentive exists to shift emissions from one stage to another. When this view is extended to the entire product life cycle, the focus is placed on strategies that reduce the total carbon footprint of the system as a whole, not any one company.

1.4 Research Questions and Approach

With this idea in mind we seek to answer the following research question in this thesis:

How do we measure the carbon efficiency of a supply chain?

To answer this we will approach the problem by answering the following three subquestions:

1. How do we define supply chain carbon efficiency?

2. What methods do we use to measure it?

3. How does it work in the context of a supply chain?

To answer these questions this thesis proceeds in three main parts. First, we develop a definition of supply chain carbon efficiency and propose an attributional approach to Life Cycle Assessment (LCA) as the appropriate method for measuring it. We then demonstrate the use of LCA to measure the carbon efficiency of a supply chain through a case study on the supply chain for bananas. Second, we analyze the uncertainty in the measurement from our case study and present a carbon label as a method for reducing this uncertainty by facilitating information sharing between firms in a supply chain. We show how information sharing can be used to provide more accurate carbon measurement through an analysis of the transportation mode and carrier selection decision. Third, we develop a model of product carbon labels to show why firms would be willing to voluntarily measure and report the carbon emissions of their products. We demonstrate how consumers that value lower carbon products can drive emissions reductions throughout the supply chain and use our model to gain insight regarding the structure of the carbon label program.

1.4.1 Definition of Supply Chain Carbon Efficiency

Based on a review of the literature, we develop a definition of supply chain carbon efficiency. This definition builds upon the existing body of work in supply chain performance measurement and eco-efficiency to present a specific metric that encapsulates the relevant aspects of environmental performance and supply chain management. We develop our definition in the context of the extended supply chain. The extended supply chain concept is common in the green supply chain management literature, but often neglected in traditional supply chain definitions that end at the consumer. Our use of efficiency draws from aspects of both supply chain performance measurement and the sustainability literature on eco-efficiency. The definition we present is compatible across different organizations, making it suitable for use in the supply chain, where data must be collected across different processes and organizations in a way that can be combined to measure the performance as a whole.

Finally, our definition is also compatible with the concept of a product's life cycle used in Life Cycle Assessment, and thus we identify LCA as the appropriate method for measuring supply chain carbon efficiency. LCA is the accepted method for measuring the carbon footprint of a product, defined as the total greenhouse gas emissions per unit of product.

This measure is in fact the inverse of the carbon efficiency of the supply chain, and so the process of measuring the carbon footprint of a product serves as a way of measuring the carbon efficiency of the supply chain. We then demonstrate the application of LCA to measure the carbon footprint of a product through a case study on the supply chain of bananas.

1.4.2 Carbon Label Framework

Based on the results of the case study and a review of sources of uncertainty in the LCA literature, we identify the lack of access to relevant data and variability in the supply chain as significant obstacles to the use of LCA to measure the carbon efficiency of supply chains. To overcome these obstacles we propose a system of information sharing between supply chain partners to provide access to relevant data that is currently unavailable or too costly for firms to acquire. However, due to the credence nature of many environmental attributes, including the carbon footprint, we identify a lack of incentive to share the true carbon footprint of products. Through the framework of a carbon label we show how a third party can increase the trust in these claims by providing services such as standards setting and certification. Using this framework we define a carbon label in terms of the three dimensions of traceability–breadth, depth, and precision.

Though this framework is useful for solving issues of data availability in the Life Cycle Assessment process, it magnifies issues related to supply chain variability. Through an analysis of transportation decision-making we show how the use of average performance measures can distort carbon footprint information and lead to poor decisions. Drawing on the concepts of management accounting we propose a system based on Activity Based Costing (ABC) to enable firms to more accurately calculate the carbon footprint of individual customers and products. We demonstrate this in the mode selection decision through the development of the carbon market area concept in intermodal transportation and with an application to truckload procurement auctions in the carrier selection step. These improved metrics make use of information available to the carrier, but not to the shipper, to demonstrate how information sharing between supply chain partners can improve the accuracy and precision of carbon footprint measurements.

1.4.3 Model of Product Carbon Labels

To gain insight as to why firms will voluntarily measure and share their carbon footprint we develop a vertical differentiation model of product carbon labels. Our model builds on existing work in the area of eco-labels by considering a label that is both voluntary and communicates a continuous value. Our model introduces two additional parameters, the cost of the label and the consumer perception of unlabeled products, that have significant impact on the final labeling decision. When consumers are willing to pay a premium for lower carbon products, firms have incentive to make costly investments in reducing emissions and communicating their carbon footprint through carbon labels.

In addition to this basic model of product carbon labels we consider two extensions. We compare the results of the basic model against a label model that certifies low carbon products, rather than communicating the exact carbon footprint. In the second model extension we address the role of upstream suppliers in the supply chain in reducing product carbon footprints. In this extended model the upstream supplier is able to contribute to the final product carbon label in two ways. First, by investing in emissions reductions in its own operations the supplier can help reduce the carbon footprint of the final product. Second, by performing a portion of the LCA needed to measure the product carbon footprint the supplier may be able to reduce the cost of the label to the downstream firm. Through the use of these models we develop insight into the actions of the third party administrator of the label and the optimal behavior of the firms in the supply chain.

1.5 Structure of this Thesis

The remainder of this thesis is structured as follows:

In Chapter 2 we review the definition of a supply chain and identify the concept of an extended supply chain as an important aspect of green supply chain management. We identify efficiency as a key measure of supply chain performance measurement and eco-efficiency as a popular metric for sustainability. Drawing from concepts in both supply chain efficiency and eco-efficiency we propose a definition of supply chain carbon efficiency as "the ratio of the supply chain output, measured by the total quantity of product produced, to be the total greenhouse gas emissions attributable to the product produced by the entire supply chain, from the source of supply through product end-of-life." The inverse of this ratio, often referred to as the carbon footprint of a product, can serve as a measure of the carbon efficiency of the supply chain.

In Chapter 3 we examine current programs designed to measure the carbon footprint of supply chains and products. The two most popular programs both specify the use of Life Cycle Assessment as the method for measuring the carbon footprint. We review the LCA methodology and identify an attributional approach to LCA as the appropriate method for measuring the carbon footprint of a product.

In Chapter 4 we present a case study illustrating the use of LCA to measure the carbon footprint of a product through an examination of the supply chain for bananas. We discuss the system boundary, the data collection process, and present the results of the study.

In Chapter 5 we identify sources of uncertainty in the measurement of carbon footprint of bananas. We show that despite significant control over the supply chain, a single company has difficulty in measuring the carbon footprint of a product. We discuss the limitations of current approaches to overcoming these difficulties and propose a framework based on the idea of a carbon label as a way of reducing these limitations. We identify the key role that third parties can play in the carbon label through services designed to facilitate sharing of carbon footprint information between firms in a supply chain.

In Chapter 6 we show how firms can measure the carbon footprint of their operations in a way that allows greater accuracy and precision than currently available methods. We propose the use of ABC to allocate emissions to products and customers in a way that supports improved decision-making within the supply chain. We demonstrate this through the development of new metrics for the mode and carrier selection steps of the transportation decision-making process. We apply the market area concept to carbon emissions in road-rail intermodal transportation to show how the use of average mode efficiencies may lead to poor decisions. In the carrier selection step we present a method for developing lane-level carbon footprint measurements for use in the carrier assignment step of a truckload procurement auction.

In Chapter 7 we provide motivation for why companies would voluntarily share their carbon footprint information through a vertical differentiation model of product carbon labels. Our model extends current labeling models by allowing for a voluntary label that communicates the exact carbon footprint of the product. We extend this model in two ways. First, we compare our model of carbon labels with a model of the more common certification-style eco-labels and identify the key differences between the outcomes of these models. Second, we extend our model of product carbon labels to a two-tier supply chain to derive insight regarding how firms in a supply chain can collaborate to reduce emissions and increase profits.

In Chapter 8 we summarize the contributions of this thesis and identify areas for future work.

Chapter 2

A Definition of Supply Chain Carbon Efficiency

In the previous chapter we introduced the idea of measuring the carbon efficiency of a supply chain as an alternative to current efforts aimed at measuring the carbon emissions of nations or corporations. In order to develop a method for measuring the carbon efficiency of a supply chain we must first develop a working definition of supply chain carbon efficiency. In this chapter we review the literature on supply chain definitions, supply chain performance metrics, and eco-efficiency to produce a definition of supply chain carbon efficiency that we will use in the rest of this thesis.

2.1 Definition of the Supply Chain

Though the key concepts of supply chain management have existed since the 1960s the term first came in use during the 1980s (Cooper, Lambert, and Pagh, 1997). In the 1990s many academics attempted to provide some structure for the emerging field (Lambert, Cooper, and Pagh, 1998), and Bechtel and Jayaram (1997) identified more than fifty existing definitions of Supply Chain Management (SCM). Many of these definitions differ in what is considered part of the supply chain. The scope of a supply chain can be defined in terms of the number of firms involved and the activities and functions involved (Cooper et al., 1997). Early definitions spanned from a firm's suppliers to its customers (Houlihan, 1985; Jones and

Riley, 1985). Stevens (1989) extended this upstream to the source of supply and downstream to the point of consumption. In their own summary of previous definitions, Lummus and Vokurka (1999) include all activities from raw materials through to the customer. This scope was considered as commonly accepted in the literature at the time (Cooper et al., 1997). While the definition and scope of the supply chain and supply chain management has evolved over time, it is still generally conceptualized as stretching from suppliers to end-users (Frankel, Bolumole, Eltantawy, Paulraj, and Gundlach, 2008). In a more recent review of 166 definitions of SCM, Stock and Boyer (2009) develop an encompassing definition of SCM with a scope from the original producer of raw materials to the final customer.

Because this definition of a supply chain is so broad it has been recognized that it is often too complex to manage in its entirety. Rarely is a firm involved in only one supply chain, but only parts of it need to be managed (Lambert and Cooper, 2000). Lambert et al. (1998) distinguish between primary members of the supply chain, who perform operational and managerial activities, and supporting members that provide resources, knowledge, utilities, or assets to the primary members. Mentzer et al. (2001) consider three degrees of supply chain complexity: the direct supply chain consists of a company, a supplier, and a customer; an extended supply chain includes suppliers of the immediate supplier and customers of the immediate customer; an ultimate supply chain includes all the organizations involved in all the upstream and downstream flows from the ultimate suppliers to the ultimate customer.

A key dimension of the management of a supply chain is that it must coordinate flows between separate firms within the product flow channel (Ballou, Gilbert, and Mukherjee, 2000). Mentzer, Stank, and Esper (2008) identify the coordination/collaboration with suppliers and customers as one of three commonalities across several definitions of SCM. Thus, given the complexity of a supply chain a firm may choose to only coordinate or collaborate with a subset of the supply chain it identifies as primary members. The primary members could even change as the firm considers different degrees of the supply chain ranging from its direct supply chain to the ultimate supply chain. Despite this focus on a subset of the supply chain we contend that the traditional definition of the supply chain itself has been accepted as extending from the upstream suppliers of raw materials through the end consumer. One area of research that has consistently used an expanded definition of the supply chain is that of green supply chain management.

2.2 Green Supply Chain Management

The focus on the environmental aspects of the supply chain often uses the term "green" (Vachon and Klassen, 2006). This represents a subset of sustainable supply chain management, which Carter and Rogers (2008) define as "the strategic, transparent integration and achievement of an organization's social, environmental, and economic goals in the systemic coordination of key inter-organizational business processes for improving the long-term economic performance of the individual company and its supply chains." Carter and Rogers's definition is based on the triple bottom line of sustainability developed by Elkington (1998) that balances economic, environmental, and social goals. Thus, green supply chain management extends traditional supply chain management by including environmental issues, which has been the leading focus of sustainable supply chain management research over the past 20 years (Carter and Easton, 2011).

Linton, Klassen, and Jayaraman (2007) identify many interactions between sustainability and supply chains that occur outside the traditional definition of the supply chain, including product use, product life extension, and product end-of-life. Srivastava (2007) defines green supply chain management as integrating environmental thinking into a supply chain that includes end-of-life and reverse logistics. Zsidisin and Siferd (2001) propose a definition of environmental supply chain management for an individual firm that includes their response to concerns regarding the environment with regard to design, acquisition, production, distribution, use, reuse, and disposal. Svensson (2007) noted that a common denominator identified across a number of isolated approaches to sustainable SCM was the need for an extended approach that moves beyond point of origin and end boundaries in descriptions of supply chains. 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, 1999a).

Thus, while Beamon (1999a) argues that the first step in a move towards sustainability is to extend the structure of the current one-way supply chain to a closed loop that includes end-of-life, this does not mean green supply chain management efforts should focus only on end-of-life issues. Van Hoek (1999) argues that a focus on reverse logistics is not enough, as green efforts can begin at the source of supply. Srivastava (2007) separates problems in green supply chain management between those that focus on green design and those that focus on green operations. The green operations problems can be further broken down into those focused on green manufacturing and remanufacturing, reverse logistics and network design, and waste management. Bowen, Cousins, Lamming, and Farukt (2001) identify two types of management activities that attempt to improve the environmental performance of purchased inputs. The first, "greening the supply process," incorporates environmental considerations into the firm's supplier management activities. The second, "product-based green supply," involves changing the product supplied. With this in mind we propose that while extending the definition of the supply chain through to end-of-life is an important issue in green supply chain management the focus should be on the environmental performance of the supply chain as a whole.

2.3 Measuring Supply Chain Performance

Gold, Seuring, and Beske (2010) argue that supply chain level capabilities are even more essential when supply chains incorporate social and environmental goals, as sustainability goals require even closer interactions between all firms involved. Seuring and Müller (2008) echo this view and identify the need for greater cooperation among partner companies as a major topic in the sustainable supply chain management literature. In making decisions for the green supply chain, non-environmental performance requirements such as cost, quality, time, and flexibility must be included so that alternatives that best support the green supply chain also make business sense (Sarkis, 2003). A major element within green SCM is the inter-organizational sharing of responsibility for various aspects of environmental performance (Hervani, Helms, and Sarkis, 2005).

One of the requirements for cooperation between firms in the supply chain is new metrics that capture inter-organizational data and express them in terms that facilitate benefits analysis (Ballou et al., 2000). Unfortunately, in a review of the literature, Lambert and Pohlen (2001) note that performance measures that span the entire supply chain may not exist, as most companies focus on individual logistics measures rather than supply chain measures. Holmberg (2000) argues that 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. Caplice and Sheffi (1994) state that developing metrics that excel across all criteria is not practically possible, and thus firms must make trade-offs in developing metrics. One of the primary trade-offs is between integrative metrics that promote coordination across the supply chain, and useful metrics that are easily understood and provide managers with direct guidance (Caplice and Sheffi, 1994). The focus on individual logistics measures may be the result of reliance on useful measures rather than integrative ones. When firms are unwilling to look beyond their own borders this represents a type of external fragmentation, and stands as a barrier to improving performance (Holmberg, 2000).

Neely, Gregory, and Platts (1995) define performance measurement as the process of quantifying the efficiency and effectiveness of action. In this context efficiency is a measure of how economically the firm's resources are utilized when providing a given level of customer satisfaction. A performance measure can be defined as a metric used to quantify the efficiency and/or effectiveness of an action. A performance measurement system can be defined as the set of metrics used to quantify both the efficiency and effectiveness of actions. Caplice and Sheffi (1995) hold a similar view, proposing that a system level measurement can be provided through a performance management system that brings together individual performance metrics. A performance measurement system plays an important role in managing business as it provides information necessary for decision-making (Gunasekaran and Kobu, 2007). Performance measurement can be analyzed at three different levels: individual performance measures, the set of performance measures as an entity, and the relationship between the performance measurement system and the environment within which it operates (Neely et al., 1995).

Numerous previous works have examined supply chain performance metrics (Chan, 2003; Gunasekaran and Kobu, 2007; Gunasekaran, Patel, and Tirtiroglu, 2001; Lambert and Pohlen, 2001; Shepherd and Günter, 2006). Traditional supply chain models have predominantly utilized two different performance measures: cost and a combination of cost and customer responsiveness. Such measurements are generally inadequate, as they are not inclusive, ignore interactions among important supply chain characteristics, and ignore critical aspects of organizational strategic goals (Beamon, 1999b). Beamon (1999b) and Lohman, Fortuin, and Wouters (2004) both propose three types of performance measures: resource measures, output measures, and flexibility measures. Efficiency is a composite resource metric that measures the utilization of resources to meet the system's objective (Beamon, 1999b). Chan and Qi (2003) also identify efficiency as a composite measure. They separate measures into three areas: input measures, output measures, and composite measures. Composite measures involve both input and output measures, and include widely employed measures such as productivity, efficiency, and utilization. Bagchi (1996) explicitly identified efficiency as one of the four categories of supply chain metrics. The popularity of efficiency as a metric may be because business activities are often modeled as transformational processes, and the three primary forms of measurement to capture the performance of a transformational process are utilization, productivity, and effectiveness. Though definitions are not consistent between all authors and fields, productivity serves as a measure of transformational efficiency and is reported as a ratio of actual outputs produced to actual inputs consumed (Caplice and Sheffi, 1994). Thus, while performance measurement may be composed of many types of individual metrics efficiency is seen as an important indicator of performance.

However, Beamon (1999a) argues that traditional supply chain performance measurements are inadequate for the extended supply chain because they do not capture environmental performance. Beamon (1999a) categorized three ways manufacturing operations impact the environment: waste (all forms), energy use, and resource use (material consumption). Within these three categories a number of individual metrics can be developed, and Hervani et al. (2005) discuss a number of indicators that may be appropriate for green SCM. Caplice and Sheffi (1994) identify eight criteria for evaluating metrics, and note that designing metrics that excel in each category is not practically possible. Instead firms must choose metrics that tradeoff between certain criteria. Clift (2003) distinguishes between formulating indicators of supply chain sustainability for applications that describe the performance of a single sector or company and those that apply to the supply chain as a whole. In developing metrics for green supply chain management we face a challenge of identifying metrics that describe the performance of the supply chain as a whole, but recognize the difficulty in inter-firm performance measurement.

One approach to supply chain environmental metrics is the environmental common denominators approach that identifies environmental themes that run across all processes and operations. These common denominators identify specific information that can be gathered across the supply chain to provide a measure of environmental performance comparable across the supply chain and within distinct functional areas (McIntyre, Smith, Henham, and Pretlove, 1998). This concept fits well with the use of productivity measures that are considered easy to obtain, readily understood, and very compatible across time and organizations (Caplice and Sheffi, 1994). The use of simple metrics may help prevent internal fragmentation, which occurs within a single firm where the effects on overall performance may be hard to understand given a number of different individual metrics that span both financial information and engineering figures (Holmberg, 2000). Thus, efficiency represents a key metric in measuring supply chain performance, but incorporating environmental considerations requires finding environmental themes that run across all organizations. One proposed method is to use the sustainability concept of eco-efficiency to compare the performance of extended supply chains for both existing and new products (Michelsen, Fet, and Dahlsrud, 2006).

2.4 Eco-Efficiency

The concept of eco-efficiency was first widely publicized by the World Business Council for Sustainable Development in 1992 (Schmidheiny, 1992). Since then it has become a key theme in sustainable development (Ehrenfeld, 2005). Despite the increased attention to eco-efficiency no consensus definition has emerged (Huppes and Ishikawa, 2005; Jollands and Patterson, 2004). The WBCSD (2000) states that "eco-efficiency is achieved by the delivery of competitively-priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the earth's estimated carrying capacity." It can be

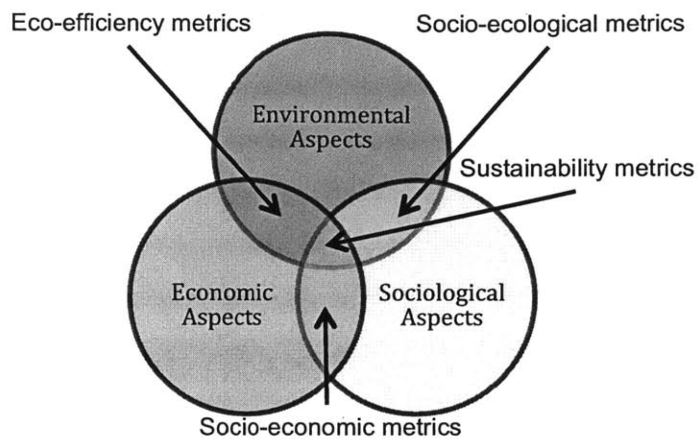


Figure 2-1: Sustainability (Sikdar, 2003)

represented by the ratio of product or service value to environmental influence (WBCSD, 2000). The concept of eco-efficiency combines performance along two of the axes of sustainability, environmental and economic (Ehrenfeld, 2005). A comparison of eco-efficiency with other aspects of sustainability is shown in Figure 2-1 (Sikdar, 2003).

The use of eco-efficiency as a measure of corporate sustainability has several shortcomings (Figge and Hahn, 2004):

- Relative measures do not give any information about effectiveness.
- Advances in environmental performance due to improved eco-efficiency can be overcompensated by other factors.
- Eco-efficiency does not cover sociological aspects.

Sustainable measures should consider both the efficiency and the effectiveness of all three dimensions of sustainability (Figge and Hahn, 2004). However, the social aspect of sustainability has generally not been well defined and has received little attention compared to the environmental and economic aspects (Hutchins and Sutherland, 2008). The operations management literature has often focused on the ecological perspective of sustainability without incorporation of the social aspects (Carter and Rogers, 2008). Thus, while eco-efficiency is not a perfect measure of sustainability it does fit within the idea of a performance measurement system, capturing two dimensions of sustainability while measuring one of the key aspects of performance.

There are a number of possible indicators that can be chosen to measure eco-efficiency, drawing on concepts from ecology, economics, and thermodynamics (Jollands and Patterson, 2004). The Global Reporting Initiative (GRI) approach proceeds from broad categories through definite aspects to specific indicators. Categories are broad areas or groupings of economic, environmental, or social issues. Aspects are general types of information related to a specific category (such as greenhouse gas emissions). Indicators are specific measurements of an individual aspect that can be used to track and demonstrate performances (Clift, 2003). This concept is employed by the WBCSD, which provides a set of generally applicable measures that can be used for all businesses to create indicators to measure eco-efficiency (WBCSD, 2000).

2.5 Defining Supply Chain Carbon Efficiency

With the ideas of green supply chain management, supply chain performance measurement, and eco-efficiency in mind we are ready to develop a definition for supply chain carbon efficiency. Our concept is based on the idea of production of a physical product, but changes could be made to support the concept of supply chains for services. First, based on the discussion of supply chain scope found in the green supply chain management literature we believe that the definition of supply chain must be extended beyond the traditional end point of the consumer. Thus, for the purposes of supply chain carbon efficiency we define the supply chain as consisting from upstream at the source of raw materials to downstream through the product's end of life.

Second, based on the concept of generally applicable indicators from the WBCSD we define the environmental influence to be the greenhouse gas emissions produced over the entire supply chain. This fits with the idea of choosing an "environmental common denominator" developed by McIntyre et al. (1998). We believe greenhouse gas emissions are a familiar concept to most firms, and thus compared to other possible environmental indicators should

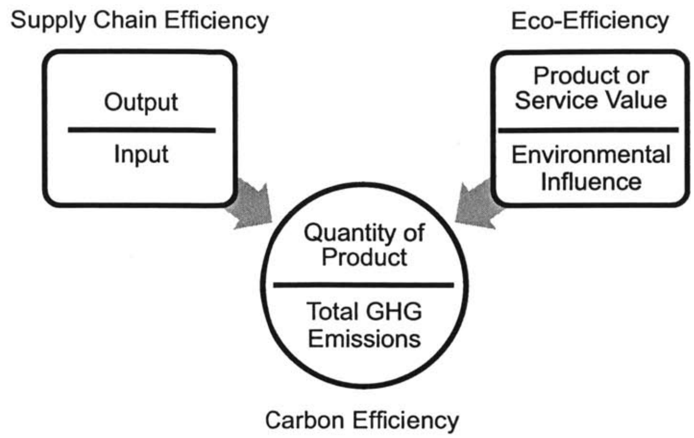


Figure 2-2: Carbon Efficiency

be easy to obtain, readily understood, and compatible across time and organizations–key strengths of productivity measures (Caplice and Sheffi, 1994).

Finally, we combine the ideas of eco-efficiency and supply chain efficiency by defining supply chain carbon efficiency as the ratio of the supply chain output, measured by the total quantity of product produced, to the total greenhouse gas emissions attributable to the product produced by the entire supply chain, from the source of raw materials through product end-of-life. This definition is depicted in Figure 2-2. This definition captures the extended scope common in green supply chain management work and recognizes that firms may be involved in the supply chain for multiple products. Thus, firms need a method to not only measure their greenhouse gas emissions, but also determine to which product those emissions may be attributed.

2.6 Conclusions

In this chapter we provided a review of key concepts from supply chain management, sustainability, and performance measurement. Using this discussion as a basis we have proposed a definition of supply chain carbon efficiency. We believe that this definition captures the relevant aspects of both green supply chain management and eco-efficiency. However, many firms may be more familiar with the inverse of this measurement, the amount of greenhouse gas emissions per product unit, which is commonly referred to as the carbon footprint of the product (Weidema, Thrane, Christensen, Schmidt, and Løkke, 2008). The inverse of eco-efficiency can be considered eco-intensity (Ehrenfeld, 2005) and is often used as an equivalent variant (Huppes and Ishikawa, 2005). Thus, the carbon footprint of a product is also a measure of the carbon efficiency of a supply chain, as reductions in the carbon footprint represent an increase in the carbon efficiency. In order to measure the carbon footprint of a supply chain it is necessary to have a method for quantifying the emissions related to the product, and in the next chapter we review current approaches for doing so and propose an appropriate method.

Chapter 3

Measuring Supply Chain Carbon Efficiency

In the previous chapter we developed a definition of supply chain carbon efficiency and introduced the idea of a product's carbon footprint serving as a measure of supply chain carbon efficiency. In this chapter we discuss current methods for measuring the carbon footprint of products and supply chains and propose the use of Life Cycle Assessment as the appropriate method for measuring a product carbon footprint.

3.1 Carbon Footprints

Despite wide use, the term carbon footprint seems to have no clear definition (Wiedmann and Minx, 2008). Based on a review of its use in literature Wiedmann and Minx (2008) propose the following definition:

> "The carbon footprint is a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product."

This definition includes only the emissions from carbon dioxide, but is applied to the full life cycle of a product. Wiedmann and Minx (2008) propose the use of "climate footprint" as a term for measures that include all greenhouse gases. This is in contrast to most definitions, which include all greenhouse gas emissions (Baldo, Marino, Montani, and Ryding, 2009; Iribarren, Hospido, Moreira, and Feijoo, 2010; Plassmann et al., 2010; Weidema et al., 2008; Wiedmann, 2009). Wright, Kemp, and Williams (2011) identify confusion surrounding this term, as the influence of a number of gases on global climate is still debated. They note that stricter definitions simply specify the six Kyoto Protocol gases, but in their own definition include only CO_2 and CH_4. Carbon footprints have been established for a number of different applications, including countries and sub-national regions, schools, products, and investment funds (Wiedmann and Minx, 2008). They can be analyzed at many different levels, including products, households, companies, cities and regions, and countries (Peters, 2010). Consistent with our focus on the supply chain of products from Chapter 2, and to avoid confusion regarding which gases are included, we define the carbon footprint of a product to include the six Kyoto Protocol gases accumulated over all life stages of a product.

Wiedmann and Minx (2008) specify Life Cycle Assessment (LCA) as the appropriate method for calculating a carbon footprint. Though recommending that the definition and method of carbon footprint should be kept separate, Peters (2010) identifies LCA as the appropriate approach for measuring the carbon footprint of consumer products. The International Standards Organization (ISO) working group identified a number of core questions regarding standardization of the quantification of carbon footprints, and even in the relatively easy class of LCA needed for carbon footprints there is no easy solution to the identified questions (Finkbeiner, 2009). The considerable flexibility allowed by the ISO standards for LCA make comparisons difficult, necessitating the development of further principles and techniques that address specific issues related to carbon footprints (Plassmann et al., 2010).

The demand for carbon footprint information and the need for further principles and techniques have lead to a number of international, national, and sectoral initiatives (Finkbeiner, 2009). Plassmann et al. (2010) identified more than thirteen different methodologies for product carbon footprinting under development in 2009. Carbon footprint measurement methodologies can be classified into three different main groups (Baldo et al., 2009):

- General guidelines, such as ISO standards, that represent the normative standard references for CO_2 calculation.

- Specific guidelines, such as PAS 2050, that contain ad hoc indication on GHG calculation and monitoring.
- Calculation tools that are aimed at calculating CO_2 emissions of specific activities.

The British Standards Institute's (BSI) Publicly Available Specification (PAS) 2050 represented the first standards for measuring the carbon footprint of products when released in 2008 (Wiedmann, 2009). Two other ongoing standardization efforts are the WRI/WBSCD's Greenhouse Gas Protocol Scope 3 standards and the ISO 14067 standards (Wiedmann, 2009). As the ISO 14067 standards are still under development, in the next section we review the currently available standards from the GHG Protocol and the revised version of PAS 2050 released by BSI in 2011.

3.2 GHG Protocol

The GHG Protocol Corporate Standard was first published in 2001, and its wide acceptance is credited to the consensus-based process adopted in its original development, followed by two years of multi-stakeholder dialogue to produce the revised edition in 2004 (Huang, Weber, and Matthews, 2009). A similar approach was followed for the development of two new standards aimed at measuring emissions across the supply chain. The Corporate Value Chain (Scope 3) Accounting and Reporting Standard (WRI and WBCSD, 2011a) (henceforth, the Scope 3 Standard) accounts for value chain emissions at the corporate level, while the Product Life Cycle Accounting and Reporting Standard (WRI and WBCSD, 2011b) (henceforth, the Product Standard) accounts for life cycle emissions at the individual product level. The Scope 3 Standard complements and builds on the Corporate Standard (WRI and WBCSD, 2004), as the Corporate Standard requires inclusion of scope 1 and scope 2 emissions, but leaves the inclusion of any scope 3 emissions as optional. The Scope 3 Standard provides guidance for calculating all scope 3 emissions, and together with the scope 1 and scope 2 emissions of the Corporate Standard all emissions in the value chain are covered. As companies are involved in supply chains for multiple products, the life cycle emissions of any one product represent only a share of the total value chain emissions. However, the

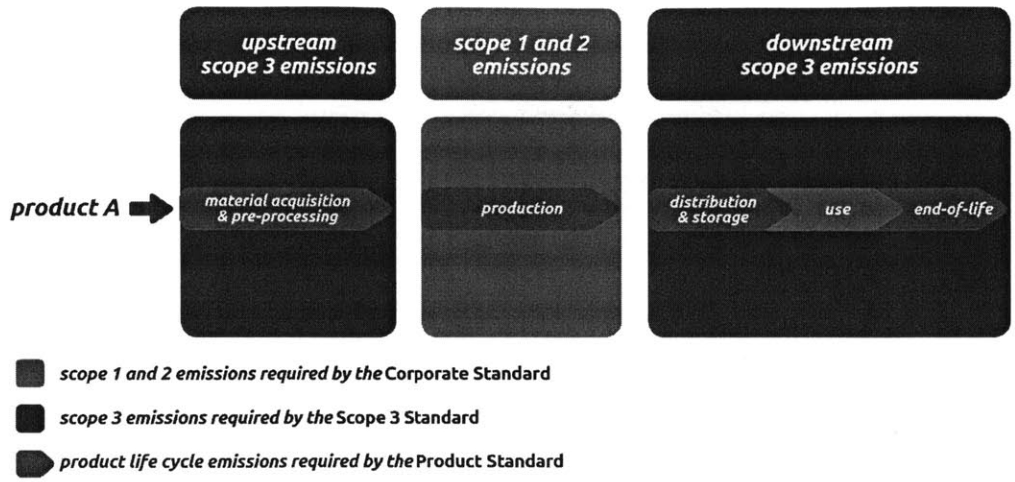


Figure 3-1: Product, Corporate, and Value Chain Comparison (WRI and WBCSD, 2011a)

sum of the life cycle emissions of all the company's products, plus some additional scope 3 emissions like employee commuting, should equal the company's total value chain emissions. This relationship is pictured in Figure 3-1.

3.2.1 GHG Protocol Product Life Cycle Standard

The GHG Protocol Product Standard (WRI and WBCSD, 2011b) provides requirements and guidance for companies and other organizations to quantify and publicly report an inventory of GHG emissions and removals associated with a specific product. The first draft of the Product Standard was developed in 2009 by Technical Working Groups consisting of 112 members representing diverse industries, government agencies, academia, and nonprofit organizations from around the world. In 2010, 38 companies from a variety of industry sectors tested the first draft and provided feedback on its practicality and usability, which informed a second draft. Members of a Stakeholder Advisory Group (consisting of more than 1,600 participants) provided feedback on both drafts of the standard.

The Product Standard is intended to support performance tracking of a product's GHG inventory and emissions reductions over time, and serves as a complement to the Value Chain Standard. While each standard can be implemented independently, both standards are mutually supportive. Possible uses of the standards together include:

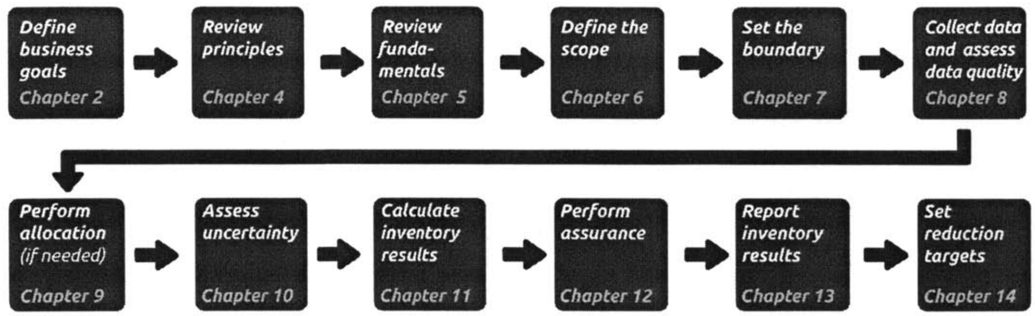


Figure 3-2: Product Carbon Footprint Process (WRI and WBCSD, 2011b)

- Applying the Corporate Standard and Scope 3 Standard (to determine the company's total scope 1, scope 2, and scope 3 emissions), using the results to identify products with the most significant emissions, then using the Product Standard to identify mitigation opportunities in the selected products' life cycles .
- Using product-level GHG data based on the Product Standard as a source of data to calculate scope 3 emissions associated with selected product types.
- Applying the Corporate Standard, Scope 3 Standard, and the Product Standard, and using the results to inform GHG-reduction strategies at both the product and corporate levels.

Implementation of the standard involves a twelve step process shown in Figure 3-2.

The Product Standard calls for a process-based LCA using the attributional approach. It builds on the requirements of the ISO standards as well as the PAS 2050 standard. Companies must account for the six main greenhouse gases, but are recommended to account for other greenhouse gases that have a 100-year GWP defined by the IPCC. The standard identifies five stages for any product life cycle: material acquisition and pre-processing, production, distribution and storage, use, and end-of-life. When processes are determined to be non-attributable, the standard allows them to be excluded from the boundary and provides guidelines on how this should be determined and reported. Examples of non-attributable processes include capital goods, overhead operations, corporate activities and services, transport of the user to the retail location, and employee transportation. For products identified as final products a cradle-to-grave boundary is specified, but for intermediate products a cradle-to-gate approach may be used when the final product is unknown.

The standard requires primary data to be collected for all processes under the company ownership or control. Companies must assess the data quality using five indicators for all processes identified as significant. The final quantification and reporting of the results is specified in CO_2e per unit of analysis, where the 100-year GWP factor is used to calculate total CO_2e. The final inventory must then be assured, either by a first or third party. First party assurance is performed by the same company reporting the results, and must be done by person(s) independent of the development of the product inventory or report. Third party assurance is provided by person(s) outside the company performing the product inventory and is considered to have a higher degree of independence and objectivity. For organizations wishing to make comparisons between products, a number of additional specifications are recommended, including identical units of analysis, equivalent boundaries, similar allocation methods, full reporting of data types, quality, and uncertainty, an assessment of representativeness, and third party assurance. The Product Standard does not support claims regarding the overall environmental superiority or equivalence of one product versus a competing product, referred to in ISO 14044 as comparative assertions.

3.2.2 GHG Protocol Corporate Value Chain (Scope 3) Standard

The primary goal of the GHG Protocol Scope 3 Standard (WRI and WBCSD, 2011a) is to provide a standardized approach to help companies understand their full value chain emissions impact in order to focus company efforts on the greatest GHG reduction opportunities. The Scope 3 Standard was developed with three objectives in mind:

- To help companies prepare a true and fair scope 3 GHG inventory in a cost-effective manner, through the use of standardized approaches and principles.

- To help companies develop effective strategies for managing and reducing their scope 3 emissions through an understanding of value chain emissions and associated risks and opportunities.

- To support consistent and transparent public reporting of corporate value chain emissions according to a standardized set of reporting requirements.

The standard is intended for companies of all sizes in all economic sectors, as well as governments, non-profits, and universities. It covers the six main greenhouse gases identified by the Kyoto Protocol, but does not address issues such as avoided emissions or actions taken to compensate for or offset emissions. Further, it is intended to compare a company's emissions over time, and is not intended to support comparisons between companies based on their scope 3 emissions. The standard was developed over a three-year process guided by a 25 member Steering Committee of experts. The first draft was developed in 2009 by Technical Working Groups consisting of 96 members. In 2010, 34 companies from a variety of industries tested the draft and provided feedback leading to a second draft. The Stakeholder Advisory Group, consisting of more than 1,600 participants, provided feedback on each draft of the standard. The process also allows for individual sectors to develop guidance through an inclusive multi-stakeholder process.

In addition to the standard, the GHG Protocol provides a companion document, "Guidance for Calculating Scope 3 Emissions", a list of data sources, and several calculation tools to assist in conducting the GHG inventory. The standard identifies fifteen categories of scope 3 emissions, separated between those upstream and downstream in the value chain, and sets minimum boundaries for each category. The categories, separated between upstream and downstream activities, are shown in Figure 3-3 along with their relation to scope 1 and scope 2 emissions. Companies collect data in each category that is either primary, directly supplied by suppliers and value chain partners, or secondary, which includes industry-average data, financial data, proxy data, and other generic data. When data is collected from suppliers or other partners the emissions may need to be allocated, and recommended approaches are given. The final reporting must include the total GHG emissions for each category in metric tonnes of CO_2e, excluding any biogenic CO_2 emissions, along with a description of the methodologies, allocation methods, and assumptions used to calculate the emissions. A number of additional reporting types are optional, including partner/supplier engagement, product performance, historic and potential future emissions, and uncertainty information.

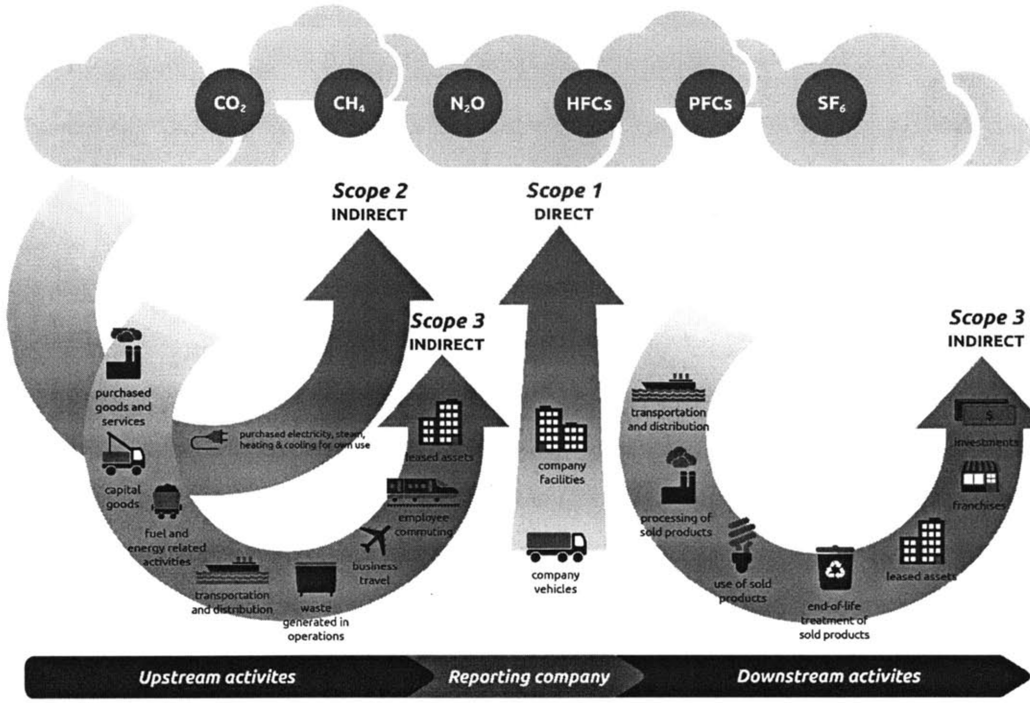


Figure 3-3: Categories of Scope 3 Emissions (WRI and WBCSD, 2011a)

3.3 British Standards Institute PAS 2050

This British Standards Institute Publicly Available Specification 2050 (BSI, 2011) is intended to benefit organizations, businesses and other stakeholders by providing a clear and consistent method for the assessment of the life cycle GHG emissions associated with goods and services. The PAS provides the following benefits:

- For organizations that supply goods and services, the PAS:
  - allows internal assessment of the existing life cycle GHG emissions of goods and services;
  - facilitates the evaluation of alternative product configurations, sourcing and manufacturing methods, raw material choices, and supplier selection on the basis of the life cycle GHG emissions associated with goods and services;
  - provides a benchmark for ongoing programmes aimed at reducing GHG emissions;

  - allows for a comparison of goods or services using a common, recognized and standardized approach to life cycle GHG emissions assessment; and
  - supports reporting on corporate responsibility.

- For consumers of goods and services, the PAS:
  - provides a common basis for reporting and communicating the results of life cycle GHG emissions assessments that supports comparison and uniformity of understanding; and
  - provides an opportunity for greater consumer understanding of life cycle GHG emissions when making purchasing.

PAS 2050 is intended for both product comparisons and communication of this information, but does not specify requirements for communication. PAS 2050 specifies that LCA shall be used to assess the GHG emissions of products. The specification distinguishes between business-to-consumer assessments, which employ a cradle-to-grave approach, and business-to-business assessments that employ a cradle-to-gate approach. Additionally, it does not include product category-specific rules, but is intended that these can be developed in accordance with ISO standards and will be adopted by the standard when available.

The Department of Energy and Climate Change, the Department for Environment, Food, and Rural Affairs (Defra), and BSI also jointly published the Guide to PAS 2050 (BSI, Defra, and DECC, 2011), which provides assistance to organizations seeking to implement PAS 2050. Additionally, the Carbon Trust published additional guides to support the robust communication of product carbon footprint information and experiences from leading companies in implementing product carbon footprinting (Sinden, 2009).

3.3.1 The Carbon Trust Carbon Reduction Label

The PAS 2050 standard recognizes a wide range of potential uses for the information on the carbon footprint of products, but does not provide requirements on the use of the assessments that arise from implementation of the specification (Sinden, 2009). It does not explicitly support comparative assertions, but recognizes that individual stakeholders may compare results that are placed in the public domain (Sinden, 2009). The Carbon Trust offers a labeling service that allows firms to communicate the carbon footprint of their product, which would allow for comparative assertions. The label was based on the original carbon footprint methodology developed by the Carbon Trust (Carbon Trust, 2007), but now offers certification against PAS 2050 or the GHG Protocol Product Standard. In order to achieve the label, firms adhere to supplementary guidelines that appear in the Code of Good Practice and Footprint Expert Guide (Carbon Trust Certification Limited, 2011).

In a 2009 review of product carbon footprint schemes the Carbon Trust Carbon Label was by far the largest of the twelve operational programs for product carbon footprints, with 2,000 certified products (Bolwig and Gibbon, 2009). The Carbon Trust claims more than 5,000 products carry the label and that it is one of the largest eco-labels in the U.K. (Carbon Trust, 2011). Thus, we distinguish between the standards that set requirements for measuring the carbon footprint of a product, and communication schemes like the carbon label that set guidelines for comparing the results of different products.

3.4 Comparison of PAS 2050 and GHG Product Standard

Both standards provide similar guidance in general but differ in certain implementations. In some cases the requirements are due to differences in the intended use. The Product Standard is intended for public reporting, and therefore includes requirements regarding specific data components that must be reported. PAS 2050 merely requires that information be recorded so that it can later be verified for conformance to the standard if necessary but does not require it to be disclosed. The Product Standard also requires a statement regarding the uncertainty be included in the report but is only guidance for PAS 2050. Additionally, a number of potential areas of discrepancy in the standards are identified, including the choice of allocation methods, materiality and cutoff rules, handling of soil and stored carbon, inclusion of specific sector guidance, choice of time horizon, and system boundary selection. In many cases the discrepancies may be alleviated through the adoption of the same category specific guidelines and through reporting guidance by programs that use the PAS 2050 specification as a basis, such as the Carbon Reduction Label. Creation of the GHG Product standard involved collaboration with the PAS 2050 creators, and this in turn influenced the revised version of PAS 2050 released in 2011 (BSI and GHG Protocol, 2011).

What is clear from both the GHG Product Standard and the PAS 2050 specification is that LCA is the appropriate method for measuring the carbon footprint of a product. Both standards specify the use of LCA and offer similar guidance on boundary selection, data collection, and quantification. Based on the definition of supply chain carbon efficiency we developed in Chapter 2, the use of LCA for carbon footprint measurement in the literature, and the requirements for the use of LCA in the two most widespread product carbon footprint programs, we propose that LCA is the appropriate method for measuring the carbon efficiency of a supply chain. In the rest of this chapter we provide a review of the LCA methodology.

3.5 Life Cycle Assessment

Life Cycle Assessment 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 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) (ISO, 2006a).

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 (ISO, 2006a).

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 two 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 (Suh et al., 2004).

3.6 Limitations of Life Cycle Assessment

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, Baumann, and Rydberg, 1994)(Suh 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 et al., 1997). The high cost and time of performing process-based LCAs poses difficulties for products with complex supply chains spanning many organizations. A survey of LCA practitioners identified data collection as the most time consuming and costly aspect of performing an LCA (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 Teno, 1996)(Huijbregts et al., 2001).

EIO-LCA provides an approach that requires less detailed process data. This work builds upon the original EIO work of Wassily Leontief (1986), 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 it. 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. 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, Joshi, and Lave, 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 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 EIO model to fill in the background processes (de Haes, Heijungs, Suh, and Huppes, 2004). The use of a hybrid method allows the EIO 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 EIO 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 that draws system boundaries and ignores processes which occur outside of the system (de Haes et al., 2004).

3.7 Conclusions

Each of the three methods discussed for performing an LCA presents 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. Despite the strengths identified for both EIO and Hybrid LCA, the PAS 2050 standard adopted a process-based approach (WRI and WBCSD, 2011b; BSI, 2011). The GHG Product Standard and the proposed ISO 14067 standards also stipulate the process method as the basic approach, but allow for use of EIO data as secondary data (Wiedmann, 2009). After reviewing the current programs and methods of LCA, we propose a process-based, attributional approach to LCA as the appropriate method for measuring the carbon footprint of a product. It underlies both the GHG Protocol and PAS-2050 standards, as well as being the most widely accepted methodology for measuring carbon footprints in environmental research (Wiedmann, 2009). In the next chapter we provide an example of how LCA can be applied to measure the carbon footprint of a product through a case study of the supply chain for bananas.

Chapter 4

Case Study: The Banana Supply Chain

4.1 Introduction

In the previous chapters we proposed the carbon footprint of a product as a measure of the carbon efficiency of its supply chain and identified Life Cycle Assessment as the appropriate method for performing the measurement. In this chapter we demonstrate how LCA can be used to measure the carbon footprint through a case study of the banana supply chain.

This study involves the cooperation of Chiquita Brands International (CBI), a leading international distributor of fruits, and Shaw's, a New England-based grocery store chain, to measure the carbon footprint of bananas using an LCA methodology. Bananas represent a significant import in the United States, with nearly 10 billion pounds imported in 2010 (USDA, 2011), and a challenging supply chain that requires getting the products to market from Central and South America in a timely manner under temperature control. Working with the partner companies, we examined the activities associated with the supply chain for any greenhouse gas emissions that might be produced. For each activity we collected data regarding the processes responsible for producing emissions. Using this data we constructed an LCA model to calculate the total carbon footprint for the product. This results of that study are presented in this chapter.

4.2 Goal and Scope Definition

The first step in an LCA is to determine the goal and scope of the study. In this section we provide a list of the objectives for this study, the primary and secondary functional units, background information on the supply chain for the product, define the system boundary, and identify the method used for quantifying the environmental impact.

4.2.1 Objective

The objective of this study is to measure the carbon footprint of bananas sold by CBI. The process involves collecting data regarding CBI's supply chain for bananas from the acquisition of materials forward to delivery to customers. Since a carbon footprint should measure the impact over the product's entire life cycle, the supply chain data was used to construct a model using the SimaPro LCA software tool. This allows estimation of life cycle impacts that occur outside CBI's supply chain, such as impacts related to upstream production of materials and end-of-life waste disposal. An additional partner, Shaw's, was able to provide data regarding supply chain activities for bananas once they have reached retail chains. Together the two companies' supply chains capture the life cycle of the banana from its production at the farm through to final sale to the end consumer.

The results of this study are by nature backwards looking, measuring the emissions attributable to bananas for operations during the year 2009. The results are not intended to evaluate the impact of specific decisions, but rather provide information about the average impact of bananas that will be useful in three ways:

1. Provide an estimate of the carbon footprint of bananas over their life cycle. This information could be used to develop a product carbon label and help influence future consumer purchases to reduce environmental impact.

2. Develop a process useable by CBI on an ongoing basis to track information necessary for developing performance metrics related to environmental impact.

3. Identify areas of high environmental impact and uncertainty in the CBI supply chain for further exploration of strategies to reduce environmental impact.

4.2.2 Functional Unit

The primary functional unit for this project is a single box of bananas delivered to a retail outlet. A typical box of bananas delivered to a retail customer consists of a cardboard container box, a plastic shroud wrapping the bananas, and approximately 18.14 kg (40 lbs) of bananas. When packed at the farm a box of bananas will hold more than 19 kg of bananas, but due to water loss during transit the weight is reduced before delivery to customers. Boxes were chosen as the functional unit since it is a common measure for quantity throughout the supply chain, avoids confusion regarding the difference in beginning and ending weight, and represents the individual unit for transactions between CBI and their retail customers.

While bananas are sold in box units to retail customers they are usually sold to end consumers by weight. For this reason 1 kg of bananas sold to the end consumer is considered to be a secondary functional unit. This functional unit is based on the assumption of 18.14 kg of bananas per box. When presenting results to consumers this may be the preferred functional unit as it represents the manner in which the product is purchased (BSI, 2011).

The functional unit is further separated between banana boxes sold in North America and Europe. While the supply chains of the two are substantially similar they are managed by different organizations and do include slightly different packaging, different methods of handling, and a significant difference in average transportation distance due to the longer ocean voyage to Europe and the larger geographic area of North America. The specific differences will be discussed in the data inventory and results will be presented for each market separately.

4.2.3 Description of Supply Chain

Bananas sold in North America and Europe by CBI are typically grown in Central and South America. CBI works with a network of owned plantations, independent growers, and wholesalers at more than 200 locations, primarily in Guatemala, Honduras, Panama, and Costa Rica (referred to generally throughout this document as "the tropics"). Though practices may vary from farm to farm, banana cultivation typically involves the application of fertilizers, pesticides, and fungicides via manual and aircraft spraying. Once the bananas approach ripeness they are picked, inspected, washed, and packaged for transportation primarily through manual labor in packing stations located at the farms. The bananas are shipped from the packing locations by truck to the outbound ocean port. In transit and at port the bananas are kept cool in refrigerated containers (primarily for North America) or bulk storage (primarily for Europe) until loading on a ship for ocean transportation.

The bananas continue to be refrigerated by container or in bulk refrigerated holds during the ocean voyage. After arriving at the destination port the bananas are unloaded from the ship and stored near the port until pickup. Customers may pick the bananas up at the ports themselves, arrange for CBI to deliver them to their facility, or CBI may take them to their own distribution centers. Upon reaching the DC the bananas undergo a chemical ripening process in a temperature controlled environment that lasts three to four days. At the end of this process the bananas are ready for sale and have a limited shelf life before over ripening. From the DC, bananas are shipped either directly to retail outlets or first to a customer DC and then to the retail outlets. At the retail outlets bananas require no special handling or care such as refrigeration. They are a fast moving product, with most bananas typically being sold within a day of arriving at the store.

In addition to the bananas themselves, a number of additional materials are used to package the bananas for transport and sale. From the packing station to North American DCs, bananas are normally shipped in container quantities. Each container holds twenty pallets of forty-eight banana boxes, for a total of 960 boxes per container. For bulk shipping bananas are typically palletized in forty-eight box lots, but the number of pallets per shipment varies depending on the size of the vehicle. In addition to the primary packing of the cardboard box and plastic shroud, secondary packing materials include cardboard corner board pieces used to help secure boxes of bananas and reusable wooden pallets. Though CBI supplies the cardboard and plastic shroud used as the primary packaging for the bananas, the retailers who purchase bananas from CBI dispose of these materials.

In addition to packaging materials a number of different chemicals are required to produce and ripen the bananas. Chemical fertilizers, fungicides, and pesticides are typically applied at the farm to help with cultivation. These chemicals are usually applied by aerial spraying or manually by farm workers. The bananas are picked before ripening and kept refrigerated during transportation. The refrigeration requires production and use of refrigerant gases, many of which are powerful greenhouse gases. Just before sale the bananas are chemically ripened in ripening rooms using ethylene gas, an organic compound that can be used to force fruits to ripen. The ethylene is purchased in liquid form and then applied to the bananas via air circulation within specially designed ripening rooms.

4.2.4 System Boundary

The system boundary chosen for this project is shown in Figure 4-1. The ideal system boundary for an attributional LCA should include the entire life cycle of the functional unit with every component traced back to its natural state. In practice such a boundary is difficult, if not impossible, to actually achieve and the ISO standards allow for the exclusion of certain stages, processes, inputs, and outputs provided it does not significantly change the conclusions of the study (ISO, 2006b).

In keeping with this definition of the system boundary the following activities are included:

- Upstream production processes for items consumed during production and distribution, including fuel, energy, farm chemicals, ethylene gas, and packaging materials.
- Fuel and energy consumption at the farm used for harvesting, chemical spraying, and packing processes.
- Fuel and energy consumed during transportation operations and in the operation of distribution facilities such as DCs, ports, and retail outlets up to and including the place of final sale to end consumers.
- End of life waste scenarios for packaging materials.
- Production and leakage of refrigerant gases.
- Production of nitrous oxide at the farm due to application of nitrogen-based fertilizer.

The following activities have been excluded from the system:

- All activities related to the use phase of the end consumer, including transportation, use, and disposal of any remaining organic matter.
  - In general bananas require no special handling, storage, cooking, or processing, so in use emissions should be minimal.
- Infrastructure, capital goods, and durable products such as pallets, roads, ports, buildings, and vehicles used during production and distribution.
- Organic waste from the bananas generated at the farm, including stalks and other material separated from the bananas during the packing process.
  - The biogenic emissions from the decay of the organic matter are excluded and likewise no credit is provided for any greenhouse gases sequestered in the product during growth.
- Rejected bananas that do not meet quality standards during the packing process are considered a byproduct.
  - All impacts from the cultivation of these rejected bananas have been allocated to the bananas that do pass quality inspection.
  - All impacts for further processing of the rejected bananas into products such as purees or ingredients are excluded from this system.
- Office buildings and other support activities not involved in production and distribution (estimated to attribute approximately 0.1% to the total carbon footprint).
- All activities related to employees, including commuting and food provided on site.
- Price tags, product stickers, and other small items estimated to have an impact of less than 1% of the total.

Though a number of different configurations of the supply chain may exist, this analysis focuses on the particular configuration where CBI transports the bananas from the port to their DC, performs the ripening, ships the bananas to the customer DC, and the customer

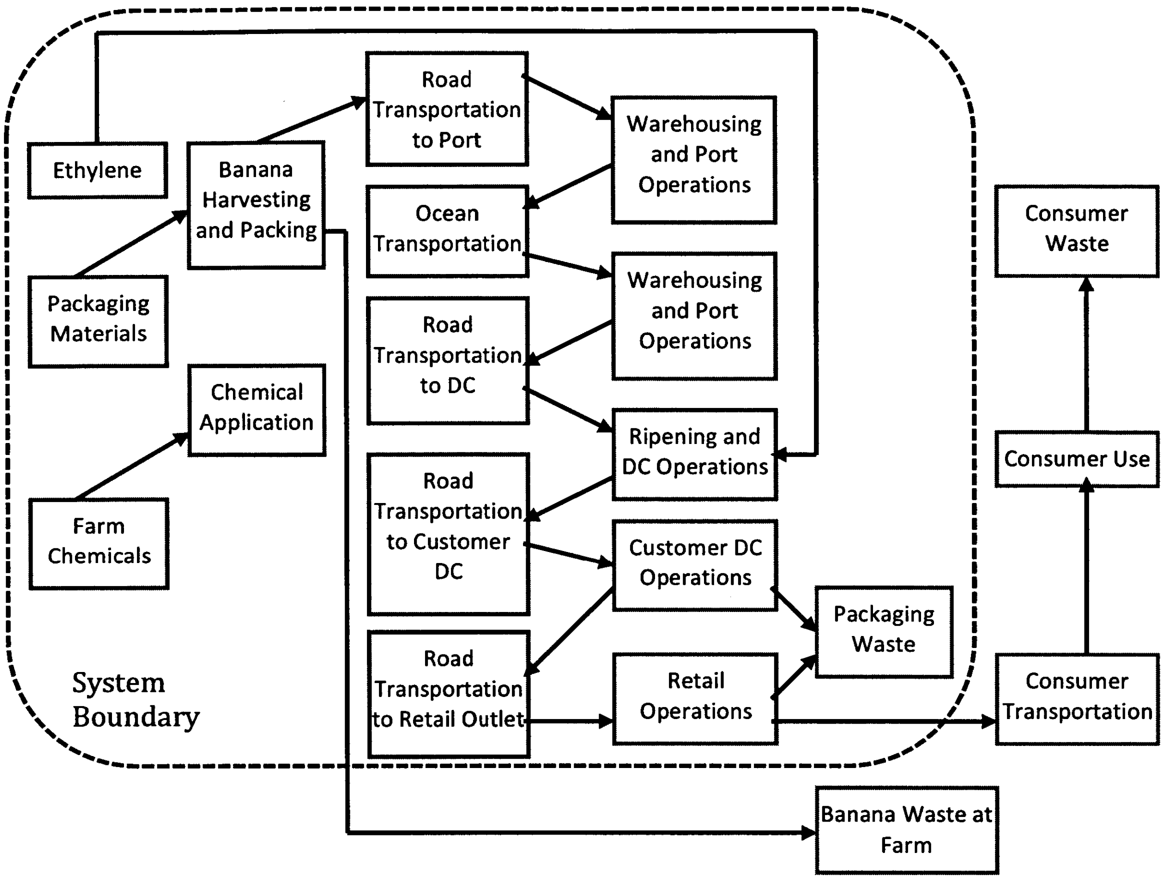


Figure 4-1: System Boundary

distributes them to the retail outlets. This configuration is generally the most complex and should provide an upper bound on the carbon footprint of the product, as other configurations generally omit at least one of the included distributions steps.

4.2.5 Impact Assessment

This project is intended to provide an estimate of the carbon footprint of the product, and therefore only a single environmental impact assessment has been performed. All impacts were assessed using the 2007 IPCC 100 year GWP method. This method provides a single measure, the estimated contribution to climate change as represented by the amount of CO_2e attributable to the system. All impacts were calculated using the IPCC 2007 GWP 100a version 1.01 method in SimaPro with the "exclude infrastructure option" selected.

4.3 Inventory Analysis and Data

The second step in an LCA is the inventory analysis. In this section we provide an assessment of the data quality collected in this study, describe the data collection for each step in the supply chain, and provide initial results from each stage of the supply chain.

4.3.1 Data Quality

Data for this project was collected from two primary sources, CBI and Shaw's. Where primary data was not available secondary sources were used, including published reports, specifications, studies, and the Ecoinvent LCA database. The quality of the data has been assessed on three criteria:

- Source—primary or secondary.
- Temporal—when was the data collected and over what period was it aggregated.
- Representativeness—how closely the data collected represents the supply chain of the system, including geographic and operational considerations.

4.3.1.1 Source

Primary data was collected for a significant portion of the supply chain through the involvement of CBI and Shaw's. The primary data collected consisted of utility records, transportation data, fuel purchase information, sales data, and specific tracked performance data such as farm yields. For packaging materials purchased by CBI, specification regarding the amount and types of materials were provided. For chemical usage CBI and Shaw's provided information regarding ethylene consumption, and CBI's agricultural division provided recommended quantities per hectare of farm chemicals. CBI provided refrigerant information based on data from maintenance records.

Secondary data sources were used for specification on secondary packaging such as cardboard corner board, plastic banana wrappers, and plastic ethylene bottles. All processes were modeled using secondary data from the Ecoinvent database in SimaPro. The data

Stage	Data
Primary Packaging Materials	Primary data regarding specification, types of material, and quantities.
Secondary Packaging	Secondary data for upstream extraction and processing.
Chemicals	Secondary data from publicly available specification for similar products.
Farm Operations	Primary data on recommended types and quantities.
Origin Port	Secondary data for modeling of upstream processing.
Ocean Transportation	Primary data regarding energy consumption and product output.
European Ports	Primary data regarding transportation distance, product quantities, and energy consumption at ports.
North American Ports	Primary data on distances, fuel consumption, and cargo quantity.
CBI DC	Primary data on energy consumption and product quantities.
Customer DC	Primary data on energy consumption and product quantities.
Retail Outlet	Primary data on energy consumption and product quantities in the USA and Europe.
Use	Primary data on electricity consumption and product quantities for one customer DC in the USA.
Disposal	Primary data on sales information and energy consumption for one store in the USA. Secondary data for consumer transport distances. Secondary data for disposal scenarios.

Table 4.1: Data Sources

sources are summarized in the table below, and more detail is given in the relevant sections later in the report.

4.3.1.2 Time Period

The intended time period for data collection was the full calendar year for 2009. Specific cases where the data was not collected for this time period include:

- Data related to customer transportation and energy consumption is based on the year 2007.
- Some ports and DCs in Europe reported data for partial periods of 2009.

- Some transportation data from the CBI DC to customer DC in Europe was provided for a subset of 2009 and was extrapolated to a full year.
- Ocean transportation cargo data is based on a set of voyages during 2009, approximately two to three weeks of data per service.
  - Fuel information and travel distances were collected for the full year and were found to be consistent with the subset of voyages for which cargo data was also available.

There are no special circumstances or changes in the supply chain known that would indicate the collected data was not representative of the intended full year 2009 timeframe.

4.3.1.3 Representativeness

Where possible, data has been collected for all of CBI's operations in order to provide a representative picture of their specific supply chain. The data is intended to model operations where CBI manages transportation and distribution from the port through to the customer DC. Areas where the data collected may not be representative include farm operations, port operations in the tropics, transportation to customers within Europe, and customer operations.

- Data for farm operations was gathered for only one of six primary growing regions in the tropics.
- Data regarding port operations was provided for only one port in the tropics region.
- Data regarding transportation to customers in Europe was provided for two of the four countries where CBI handles transportation.
- Data was provided by only one customer in the U.S. and none in Europe.

A summary of the representativeness of data collected at different stages is shown in Table 4.2. Several alternative scenarios were considered in a sensitivity analysis performed to address issues of representativeness.

Stage	Data
Chemicals	Average recommended usage across all six growing regions.
Farm Operations	Average data for more than thirty farms, but only within one growing region.
Origin Port	Data for only one of six ports in the tropics.
Ocean Transportation	Data for five of six ocean services, averaged across services due to limited time horizon of data.
European Ports	Data for all ports.
North American Ports	Data for four of five ports.
European Transportation	All shipments from Port to DC. Data for transportation to customer in two of four regional markets. Average statistical data for customer transportation.
North American Transportation	All shipments from Port to DC and to customers. Customer transportation for one retail customer.
CBI DC	Data for six of nine DCs in the USA. Data for ten of eleven European DCs.
Customer DC	Data for only one customer in the USA, none in Europe.
Retail Outlet	Data for only one store of one customer in the USA, none in Europe.
Disposal	Average disposal scenarios for USA and England.

Table 4.2: Data Representativeness

4.3.2 Loss Rates

Data has generally been collected and reported based on production quantities rather than final sales numbers to customers. Since the functional unit chosen for this study was a box of bananas delivered to the retail customers the results must be adjusted to account for loss during operations. Based on an estimate reported by CBI the loss rate was assumed to be 4%. That is, for every 100 boxes produced by CBI only 96 will end up sold to customers, with the other four lost, damaged, or rejected by the customer. This is reflected in the reported emissions numbers by first calculating results per box based on production data and then multiplying by 1.0417 (100/96) to account for allocation of the total emissions to only sold bananas. Throughout this report all data is reported per box produced while results are presented per box sold, reflecting the adjustment due to loss.

4.3.3 Transportation

Transportation in the banana supply chain can be separated between ground transport performed by trucks in the tropics and destination markets and the ocean voyage that brings the bananas to market from the tropics.

4.3.3.1 Ground Transportation

Ground transportation of the bananas includes shipping from the farm to the outbound port, inbound from the destination port to the CBI DC, from the CBI DC to the customer DC, and outbound from the customer DC to the retail store. Additional ground transportation in the system includes delivery of chemicals and packaging materials to the farm and ethylene ripening fluid to the CBI DC.

Data

Tropics Shipping distance from the farm to port can vary based on where the farm is located and which shipping port was used. Transaction level data for each shipment was not available; instead an average distance to port was calculated based on logistics

	Guatemala	Honduras	Nicaragua	Costa Rica	Panama	Colombia	Ecuador
Total km traveled	29,554,975	4,411,562	3,829,143	10,710,321	3,669,115	-	-
Equivalent Containers	54,244	26,003	3,528	41,949	16,142	21,572	18,412
Total boxes	28,043,772	11,425,631	1,661,320	24,256,076	15,265,841	17,737,773	17,675,316
To EU boxes	0	0	0	0	15,265,841	17,737,773	17,675,316
To NA boxes	28,043,772	11,425,631	1,661,320	24,256,076	0	0	0
Avg. km per container	545	170	1,085	255	227	-	-
Avg. boxes per container	517	439	471	578	946	822	960

Table 4.3: Ground Transportation From Farm to Port

data provided by CBI's operations in the tropics for eight different countries (Guatemala, Honduras, Nicaragua, Costa Rica, Panama, Colombia, and Ecuador). This data included the total kilometers traveled for all shipments (except in Colombia and Ecuador where this data was not provided), the number of equivalent containers moved, and the total number of boxes shipped to North America and Europe for each country. From this data the average distance per shipment for each country was calculated by dividing the total km by the number of equivalent containers shipped, providing an average distance per equivalent container. Average truck utilization was calculated by dividing the total number of boxes shipped by the number of equivalent containers to determine the average number of boxes per shipment. The average distance and boxes per shipment for North America bound shipments were calculated by averaging the results from the four countries that supplied North America (Guatemala, Honduras, Nicaragua, and Costa Rica). The data for Panama was used as the average distance for Europe-bound shipments due to the lack of distance data for the other sourcing countries, Colombia and Ecuador. Emissions from the shipment were then allocated based on the average number of boxes per shipment.

North America Shipping distances at the destination side similarly can vary depending on the exact path traveled by the bananas. Data provided by the North American logistics teams included the total number of shipments, the total number of boxes shipped, the total distance traveled, and the average fuel consumption of the vehicles used. This was further broken down between shipments from the port to DCs and from DCs to customers. The shipping data is based on records from all five ports and nine DCs in North America and includes shipments to more than 300 customer locations.

The average shipment distance was calculated by dividing the total distance by the

Origin	Destination	Total # of Shipments	Total Distance (km)	Total Boxes
Port	DC	9,991	4,255,568	10,586,392
DC	Customer	6,374	2,806,902	4,036,569

Table 4.4: Ground Transportation Data, NA Ports and DCs

number of shipments, producing an average distance traveled per shipment of 426 km from the port to the DC and 440 km from the DC to the customer. The average number of boxes per shipment was 1,060 from the port to the DC and 633 from the DC to the customer, and was calculated in a similar manner. Emissions from the shipment were then allocated based on the average number of boxes per shipment.

Data on transportation for customers from the DC to the retail outlet in North America was provided by Shaw's. This data included the total distance driven for all shipments in a year, the number of shipments, the total number of banana boxes delivered, and the percentage of all shipments composed of bananas as measured by volume. Using this data the average distance per shipment of 118 km was calculated by dividing the total distance driven by the number of shipments. Emissions from the shipment were allocated based on the average of eighteen boxes of bananas per shipment and 5.4% of the shipment volume being made up of bananas. With eighteen boxes of bananas per shipment representing 5.4% of each shipment volume, the average total shipment volume is equivalent to 333 boxes of bananas.

While data from only a single grocery chain was available, previous work has noted that distribution patterns are consistent across firms within regions. Typical distribution radiuses for supermarket chains would be 50-100 miles in the eastern United States and 100-150 miles in the west (Ellickson, 2007). The average distance to stores calculated for Shaw's was about 70 miles, consistent with the reported values for the eastern United States.

Europe The European logistics team provided data for shipments from ports to DCs where CBI managed the transportation. This consisted of records for more than 6,000 shipments and seven million boxes of bananas. Data consisted of the origin port, destination DC, total number of shipments, total number of banana boxes, and distance between the origin and destination. A sample of the data is shown in Table 4.5. The average shipments

Port	DC	# of Shipments	Total Boxes	Distance
Antwerp	Gdynia	323	372,004	1,226
Antwerp	Katowice	329	378,473	1,218
Antwerp	Kalisz	359	414,056	1,170

Table 4.5: Ground Transportation Data, EU Port to DC, Sample

distance was calculated using the distance of each origin-destination pair weighted by the total number of boxes shipped on that route. The emissions from the shipment were allocated based on the average number of boxes per shipment.

CBI operates DCs in five European regions, but only manages transportation from those DCs in four regions: the U.K., the Netherlands, Poland, and Belgium. CBI provided data on shipments from the DC to customers for two of those regions, the U.K. and Poland. The data for the U.K. was based on a sample of one week's shipments while the data for Poland included six months of shipments. In each region the data included the total distance of the shipments, the total number of boxes shipped, and the total number of shipments. The average shipment distance was calculated using the total distance and the total number of shipments. The average shipment size was calculated by dividing the total boxes shipped by the number of shipments. The emissions for the shipment as a whole were allocated based on the average number of boxes per shipment.

No data for shipments from the customer DC to the retail outlet was provided. Instead, an average shipment distance was calculated based on information supplied by Eurostat, the European statistical office, and sales data provided by CBI. The Eurostat database contains information on the food supply chain for the EU-27 members. This data includes the transport volume for "potatoes, other fresh or frozen fruits and vegetables" for the EU-27 countries based on the distance shipped within ranges of 0-49 km, 50-149 km, 150-499 km, or greater. Volumes were assumed to be uniformly distributed within a range, while shipments greater than 499 km were assumed to average 700 km per shipment. Using these assumptions and the percentage of shipments within each range, an average shipment distance was calculated for each country. CBI provided sales data that included the volume of banana boxes sold within each European country. Using the sales volume for each country along with the calculated shipping distance for that country a weighted average distance of

193 km was calculated across the EU-27 countries. Vehicle utilization was assumed to be equal to North America, 333 boxes per shipment, and emissions from the shipment were allocated to the functional unit based on this assumption.

Refrigeration Equipment In addition to fuel consumption required for vehicle operation, ground transportation of bananas requires refrigerated containers to prevent ripening during transit. The operation of the generators (referred to as gensets) that supply electricity for the refrigeration equipment in the containers consumes approximately one gallon of diesel fuel per hour of operation based on estimates provided by Shaw's and CBI. Speed estimates from Shaw's indicate an average speed of about 36 mph including loading, unloading, and transportation times. Using these estimates, fuel consumption due to refrigeration for all ground transportation stages was calculated based on the distance traveled, average speed, and fuel consumption per hour. Emissions from the refrigeration were allocated based on the average number of boxes per shipment.

Packaging and Material Shipments Additional ground transportation emissions were calculated for shipment of the ethylene fluid from the distributor to the DC, packaging materials delivered to the farm, and for chemicals from a distributor to the banana farm. The ethylene fluid shipment travel distance was estimated using Google maps functionality to calculate the driving distance from the distributor's city to each DC. The average distance was then calculated by weighting the distance by the number of boxes processed at each DC as reported by CBI sales figures. Packaging materials are delivered to the farms on the backhaul leg of journeys from the farm to the port, so the average distance calculated for the farm to port banana shipment was used as the shipping distance of the packing materials as well. Chemical shipments to the banana farms vary depending on the location of the farm and the source of the chemicals. This distance was assumed to be 100 km for the purpose of this study, as no data has yet been collected on actual shipping distances.

Results The results from all ground transportation operations are shown in the table below. The largest contributor to emissions for both the North American and European case was the trip from the DC to the customer. The higher vehicle utilization achieved

Stage	North America	Europe
Farm to Port (Truck)	0.6	0.3
Farm to Port (Genset)	0.2	0.1
Port to DC (Truck)	0.5	0.7
Port to DC (Genset)	0.1	0.1
DC to Customer (Truck)	0.8	0.6
DC to Customer (Genset)	0.2	0.1
Customer to Store (Truck)	0.4	0.6
Customer to Store (Genset)	0.1	0.1
Packaging Shipment	0.1	0.1
Fertilizer Shipment	0.0	0.0
Ethylene Shipment	0.0	0.0
Total	2.8	3.0

Table 4.6: Emissions from Ground Transportation (kg CO_2e/box)

during full truckload shipments from the port to the CBI DC reduces the overall impact on a per box basis despite similar trip lengths in North America and longer trips in Europe. As distances between ports, DCs, and customers can vary significantly, a comparison of the average distance to the minimum and maximum shipment distance were included in the sensitivity analysis.

4.3.3.2 Ocean Transportation

Bananas are shipped between the tropics and destination ports in North America and Europe on a series of ocean shipping rotations. Each shipping rotation visits a regular series of ports on a defined schedule. The primary purpose of the shipments is the delivery of bananas to the destination market, but some cargo is also shipped back to the tropics during the return (backhaul) portion of the voyage.

Data CBI provided shipment data for one complete shipping rotation for each of the three European services and two full rotations for two of the three North American services. This data included the shipping distance, cargo weight, and fuel consumption during each leg of the voyage. The total tonne-km (tkm) of cargo shipped was calculated by multiplying the distance in kilometers by the cargo in tonnes for each leg of the rotation, including the backhaul. The ocean data provided for the Gothenburg-Bremerhaven service is shown in the

From	To	Cargo (Tonnes)	Distance (Nautical Miles)	Fuel, Propulsion (Tonnes)	Fuel, Auxiliaries (Tonnes)	Tonne-km	Total Fuel (Tonnes)
Almirante	Moin	6223	65	7.0	1.3	749,125	8.3
Moin	Gothenburg	8301	5410	663.5	46.4	83,170,375	709.9
Gothenburg	Bremerhaven	6211	349	41.8	3.8	4,014,467	45.6
Bremerhaven	Almirante	1850	5149	561.3	41.0	17,641,504	602.3

Table 4.7: Sample Ocean Data

Service	Fuel (tonnes)	Cargo (tonne-km)	Fuel Efficiency (g/tkm)
Wilmington-Gulfport-Freeport	1,054	100,521,756	10.5
Port Everglades	360	35,390,431	10.2
Gothenburg-Bremerhaven	1,366	105,575,471	12.9
Sheerness-Antwerp	1,214	89,041,451	13.6
Southern	1,443	89,586,805	16.1
Average	1,087	84,023,183	12.9

Table 4.8: Fuel Efficiency by Service

table below as a sample.

Using this data the fuel consumption (propulsion and auxiliaries) from the operation of the vessel was calculated per tonne-km of goods shipped by adding the results from each leg to calculate the total fuel consumption and tonne-km for the rotation, including backhaul. This process was repeated for each service, and total average fuel consumption per tonne-km was calculated for all services together.

Shipping distance for each destination port was calculated from the first port on the rotation through to the destination port using the data provided by CBI. For ports that were not included on the rotations provided in the data, distances were calculated using sailing schedules provided by CBI and distances between ports calculated using www.dataloy.com. Using the data from Gothenburg-Bremerhaven as an example, shipments were assumed to originate in Almirante and distances were calculated as 5,475 nautical miles to Gothenburg and 5,824 to Bremerhaven. This distance was calculated for every destination port and a weighted average for North America and Europe was calculated based on the volumes shipped to each destination port.

Fuel consumption for boxes sent to each destination port was calculated by multiplying

Destination Port	Distance (km)	Share of Volume
Antwerp	9,443	29%
Bremerhaven	10,786	25%
Gothenburg	10,140	13%
Aegion	13,451	7%
Vado	11,958	8%
Civitavecchia	12,342	11%
Setubal	9,666	3%
Sheerness	9,354	4%
Average	10,651	

Table 4.9: European Ocean Shipping Distances

Destination Port	Distance (km)	Share of Volume
Hueneme	3,880	22%
Everglades	1,671	12%
Gulfport	1,882	23%
Freeport	2,909	6%
Wilmington	5,593	37%
Average	3,737	

Table 4.10: North American Ocean Shipping Distances

the distance to the port by the weight of the boxes in tonnes to find the total tonne-km. This figure was multiplied by the average efficiency of 12.9 g/tonne-km to calculate total fuel consumption per box. Average weight per box was provided by CBI as 20.2 kg for North America and 20.9 kg for Europe. This figure is based on the total weight of bananas, their packaging, and pallets divided by the number of boxes.

Packaging Estimates In addition to shipment of bananas to the destination ports, the ocean vessels are also used to deliver packaging materials to the tropics. Based on information from CBI the materials are produced in the United States shipped out of Gulfport on the return voyage of the banana vessels for delivery to the farms in the tropics. The distance for the shipment and the weight of the packaging and pallets are assumed to be identical to the shipments of bananas to Gulfport. The calculation of the average fuel consumption per tonne-km in the previous section was based on the overall average performance of the shipping rotation, which included the backhaul utilization, and so the same average fuel consumption factor was applied to shipment of the packaging. Emissions are allocated to

Stage	North America	Europe
Banana Shipment	3.6	10.6
Packaging Shipment	0.0	0.0
Total	3.6	10.6

Table 4.11: Emissions from Ocean Transportation (kg CO_2e/box)

the bananas based on the assumption of one box and shroud per banana box, one set of corner board per pallet, and one pallet for every forty-eight banana boxes.

Results The emissions from the ocean shipping of the bananas represent a significant source of emissions in the supply chain, particularly in the case of Europe. The average distance for shipments destined for Europe is three times as great as for the average shipment to North America, producing the much higher emissions value.

4.3.4 Facilities

Four types of facilities are involved with producing and distributing bananas:

- Farms where the bananas are grown and packaged.
- Ports where they are loaded and unloaded from ships and may be stored temporarily.
- Distribution centers that store and ripen the bananas. May be operated by CBI or the retail customer.
- Retail outlets where the bananas are sold to end consumers.

4.3.4.1 Distribution Centers

Distribution centers are used to store the bananas and provide chemical ripening before shipping to the customer DC or the retail outlet. Operations at the DC requiring energy may include: heating, cooling, and lighting of the facility; electricity and propane to power cargo handling equipment; diesel burned in trucks moving containers; and electricity to power the banana ripening rooms. CBI DCs primarily handle bananas, with other products such as plantains and pineapples making up less than 1% of volume. The Shaw's DC, however,

DC	Boxes	Electricity (kWh)	Propane (lbs)	Diesel (gallons)	Fuel Oil (gallons)	Natural Gas (100 ft3)
Boston	1,032,947	597,289	2,345	0	0	1,243
Mid Atlantic	2,439,871	1,215,600	0	23,158	10,000	0
Atlanta	1,179,638	432,766	0	0	0	5,669
Miami	4,806,068	3,508,320	4,824	70,856	0	0
Gulfport	978,686	1,117,080	0	0	0	0
Los Angeles	2,922,417	511,280	0	66,040	0	0
Total	13,359,627	7,382,335	7,169	160,054	10,000	6,912

Table 4.12: North American CBI DC Data

Location	Boxes	Electricity (kWh)	Allocation %	kWh/Box
New England DC	1,161,600	6,045,000	5.4%	0.28

Table 4.13: North American Customer DC Data

handles all perishable goods sold at their stores. Bananas are high volume products and have a separate room for storage and ripening within the facility. This room is kept chilled, but at a higher temperature than other parts of the facilities which handle frozen and refrigerated products.

Data

North America CBI operates nine DCs within the United States. Energy consumption was calculated for six of those DCs based on their utility bills and purchase records for a one year period. The total number of banana boxes processed in each facility was calculated based on sales data. An average consumption of each energy source per box was calculated for each DC separately and for the total of all five reporting DCs together.

Shaw's provided utility data for electricity consumption and banana sales data for their perishable DC over a one year period. Energy consumption in the DC was allocated to bananas based on the percentage of square footage of the facility occupied by the banana room. The emissions from this share of the facility energy consumption were then allocated based on the total boxes of bananas sold by Shaw's in the year.

Facility	Electricity Consumption (kWh)	Boxes	Electricity per box (kWh / box)
Dewsbury	718,306	1,196,530	1.67
Sheerness	584,333	440,363	0.75
Puurs	1,011,781	1,687,074	1.67
Gorinchen	499,153	764,305	1.53
Meppel	226,993	325,400	1.43
Helsingborg	512,367	674,795	1.32
Enkoeping	371,820	545,967	1.47
Katowice	426,312	456,000	1.07
Gdynia	370,303	533,000	1.44
Kalisz	364,197	473,000	1.30

Table 4.14: European CBI DC Data

Distribution Center	North America	Europe
CBI DC	0.5	0.8
Customer DC	0.2	0.1
Total	1.2	0.9

Table 4.15: Emissions from Distribution Centers (kg CO_2e/box)

Europe CBI operates eleven DCs in five different European countries, the U.K., Sweden, Poland, the Netherlands, and Belgium. Electricity and banana sales data were reported for a six month period for ten of the eleven DCs. Average electricity consumption per box was calculated for each DC as well as an overall average using the total kWh consumption and sales data for the ten reporting facilities. No data was provided for customer DCs in Europe. Electricity consumption was assumed to be the same as the North American data on a per box basis.

Results The results for the DCs are shown below. Emissions at the CBI DC are significantly higher on a per box basis than at the customer DC due to higher utilization of the Shaw's DC. While both Shaw's and individual CBI DCs handle similar volumes of bananas, this represents only a small fraction of the total material handled by the perishable DC, and this higher utilization more than offsets the higher total energy consumption of the facility.

Electricity (kWh)	Natural Gas (cubic ft)	Allocation %	Boxes	kWh/box	Cubic ft/box
2,536,490	39,867	0.65%	5,760	2.86	0.04

Table 4.16: North American Retail Outlet Data

4.3.4.2 Retail Outlets

Bananas typically require no special handling at the retail outlets, but electricity and natural gas are consumed at the store for heating, lighting, office equipment, checkout registers, and other activities required to run the store. At Shaw's bananas may be delivered to the store on a nearly daily basis. Once they arrive they are usually placed in a storage room with other produce and used to restock the banana display on the sales floor several times per day.

Data

North America Utility and sales data were collected from one of Shaw's retail store that was considered to be representative of an average store. The energy data included total electricity and natural gas consumption for one year. Sales data included the total store sales volume in dollars, banana sales in dollars, and banana sales in boxes for the year. For this phase an allocation based on the economic value of products sold was used. A retail grocery store sells thousands of different products, and allocating based on other means requires significant amounts of information that are typically not available. Sales information is readily available, however, and energy was allocated based on the percentage of total store sales represented by bananas. The energy consumption was then allocated to individual banana box level by dividing the allocated energy by the total boxes of bananas sold at the store during the year.

Europe No data from a European retailer has been collected yet. Instead it was assumed that per box consumption of electricity and natural gas was the same as in the case of North America.

Store	North America	Europe
Retail Store (Electricity)	2.3	1.5
Retail Store (Natural Gas)	0.0	0.0
Total	2.3	1.5

Table 4.17: Emissions from Retail Outlet (kg CO_2e/box)

Results Emissions from energy use at the retail store are shown in the table below. Nearly all emissions are the result of electricity usage, as the small amount of natural gas used does not produce significant emissions. Emissions from the store are higher than at the DCs due to the greater efficiency of DCs. A single distribution center may process the same number of bananas as are sold at hundreds of stores, and while energy consumption in total is higher at the DC it is lower on a per box basis. Emissions in Europe are again lower due to the lower emissions intensity of the average European electricity production process.

4.3.4.3 Port Operations

Facilities at the port can include a refrigerated storage building, offices, and a container yard used for storing and powering the reefer containers. Activities that generate emissions may include powering facilities, drayage operations involving trucks moving containers within the yard, and operation of heavy equipment cargo equipment. The exact usage depends on the infrastructure and operations at the ports involved.

Data

North America The North American logistics team provided electricity and diesel consumption data for one year for all ports except Freeport. Data on the number of boxes handled at each port were based on reported shipments via ocean to each port. Electricity and diesel consumption were calculated per box at each port and then an average for all ports was calculated based on total consumption and boxes handled.

Europe The European logistics team provided data for ten destination ports in Europe. This data included the total electricity, natural gas, and diesel fuel consumed as well as the total boxes handled during a given time period. Average energy consumption per box

Port	Boxes	Electricity (kWh)	Diesel (gallons)	kWh/box	Gallons/box
Wilmington	23,319,318	8,927,829	31,450	0.383	0.001
Gulfport	14,449,053	8,345,262	1,548	0.578	0.000
Port Everglades	7,352,312	6,981,832	41,226	0.950	0.006
Hueneme	14,087,360	2,620,020	0	0.186	0.000
Total	63,166,010	26,874,943	74,974	0.425	0.001

Table 4.18: North American Port Data

Port	Weeks of Data	Boxes	Share	Electricity (kWh)	Natural Gas (liters)	Diesel (liters)	Electricity (kWh/box)	Natural Gas (liters/box)	Diesel (liters/box)
Sheerness	20	2,189,338	3%	757,175	0	0	0.35	0.00	0.00
Bremerhaven	25	7,003,378	25%	1,636,000	450,000	0	0.23	0.06	0.00
Antwerp	52	12,938,755	24%	2,239,696	0	83,523	0.17	0.00	0.01
Vado	34	3,571,894	9%	129,500	0	0	0.04	0.00	0.00
Civitavechia	52	4,571,458	11%	945,392	0	0	0.21	0.00	0.00
Setubal	-	2,496,000	3%	210,525	0	7,800	0.08	0.00	0.00
Aegion	34	3,122,265	7%	351,393	0	0	0.11	0.00	0.00
Gothenburg	52	6,240,000	16%	1,594,360	0	84,340	0.26	0.00	0.01

Table 4.19: European Port Data

was calculated for each port during the given timeframe, and then an overall average was calculated based on the share of boxes handled by each port during the full year as reported by ocean shipping data.

Tropics Energy consumption data was collected for one origin port in the tropics, Puerto Limon in Costa Rica, based on fuel and electricity purchase records for the year. This was separated into fuel consumed for truck operation at the port, operating heavy equipment, powering generators, and electricity used in the container yard. Emissions were allocated per box using the total number of boxes shipped from the port during this time period. Data for other ports was not yet available and was assumed to be the same as for Costa Rica.

Results Results for port operations from all three regions are shown below. Emissions from Europe are lower primarily due to the reported low energy consumption per box. North American and Costa Rica showed similar electricity consumption per box, but the electricity generation in Costa Rica is significantly lower in emissions intensity than in the

Category	Energy Source	Total Consumption	Total Boxes	Per Box
Heavy Equipment	Diesel (liters)	307,047	12,121,430	0.03
Container Yard	Electricity (kWh)	11,643,348	12,121,430	0.96
Generators	Diesel (liters)	364,412	12,121,430	0.03
Truck Operation	Diesel (liters)	123,766	12,121,430	0.01

Table 4.20: Costa Rica Port Data

Source	North America	Europe	Costa Rica
Electricity	0.4	0.1	0.1
Heavy Equipment	0.1	0.1	0.1
Truck Operation	0.0	0.0	0.0
Generators	0.0	0.0	0.1
Natural Gas	0.0	0.0	0.0
Total	0.5	0.2	0.3

Table 4.21: Emissions from Port Operations (kg CO_2e/box)

United States.

4.3.4.4 Farms

In addition to the energy consumption at the distribution facilities, farms consume energy during the cultivation and packing of bananas. Though banana farming still relies heavily on manual labor, energy is needed to power farm equipment, spray chemicals, and power packing stations.

Data Practices vary between farms, and at this time data regarding the energy consumption at each farm was not available. Instead total data was provided for all farms in one growing region in Costa Rica. This region contains more than thirty farms and produced more than twelve million boxes in 2009. This data includes fuel records for diesel used to run generators and farm equipment, electricity purchased from the grid for powering packing stations and offices, gasoline and diesel used in vehicles, and estimates of fuel consumption by airplanes used to spray chemicals. Total fuel and electricity consumption were allocated per box by dividing the total consumption by the number of boxes produced by the region during the year.

The company that operates the agricultural spraying service provided estimates for the

Activity	Fuel	Consumption	Boxes Produced	Consumption per box
Building Power	Electricity (kWh)	5,536,529	12,121,430	0.46
Vehicle Operation	Diesel (liters)	15,910	12,121,430	0.00
Vehicle Operation	Gasoline (liters)	12,091	12,121,430	0.00
Aircraft Spraying	Diesel (liters)	847,454	12,121,430	0.07
Generators	Diesel (liters)	63,266	12,121,430	0.01
Generators	Gasoline (liters)	10,415	12,121,430	0.00

Table 4.22: Data from Farm Operations

Source	CO_2e
Electricity	0.0
Vehicles (gas)	0.0
Vehicles (diesel)	0.0
Generators	0.1
Aircraft	0.2
Total	0.3

Table 4.23: Emissions from Farm Operations (kg CO_2e/box)

fuel consumption of the airplanes used during the spraying process. This approximation was based on an estimate of the amount of fuel required to spray one hectare of farmland. Total consumption was then calculated by the farm operations team based on total number of hectares sprayed during all spraying operations for the year. Emissions from spraying were allocated per box based on the total production for the year.

Results Emissions from farm operations are shown in the table below. The fuel consumption due to aerial spraying is the primary source of emissions due to operations at the farm. The low emissions intensity of electricity generation in Costa Rica keeps emissions from the packing station low. A comparison of electricity emissions intensities of other growing regions were included in the sensitivity analysis.

4.3.5 Materials

Emissions related to the production of materials used in the supply chain can be placed in to two categories: packaging materials and chemicals. The primary packaging materials included in the analysis were the cardboard banana box, the plastic shroud used to wrap bananas inside the banana box, and the cardboard corner board used to help stabilize the boxes of bananas for transport. In addition to the primary packaging, the plastic banana wrapper used to protect the banana bunches during cultivation is included, as well as the plastic bottle used to hold the ethylene fluid used for ripening. The chemicals used in the supply chain include the pesticides, fertilizers, and fungicides used at the banana farms along with the ethylene fluid used to ripen the bananas at the DC.

4.3.5.1 Packaging

The primary packaging for the bananas consists of a plastic shroud used to enclose the bananas and a cardboard box that the shroud and bananas are placed within. Boxes of bananas may then be stacked on pallets, typically with forty-eight boxes per pallet. Cardboard corner board may be placed on the edges of the stacked banana boxes to provide stability during transit. The wooden pallets used during shipping are durable goods that are collected and reused, and their production and disposal is excluded from this study.

Data Data for the box and shroud is based on specifications provided by CBI to the companies that produce the packaging. This data includes the type of material for the packaging as well as the weight of the product. The banana box has three different models: one for North American container shipment, one for North American bulk shipping, and one for European boxes. Each box is constructed of the same corrugated cardboard but differ in dimensions and final weight. The plastic shrouds likewise differ between the North American and European markets, with the North American shroud produced from high-density polyethylene (HDPE) plastic and the European one from low-density polyethylene (LDPE) plastic. No data was provided regarding the cardboard used in the corner board. Instead, an assumption of 0.61 kg of recycled cardboard was used based on published numbers for a similar product (Alliance Plastics).

Results The results from each of the three packaging scenarios are shown in Table 4.25. The plastic shroud is identical between the two North American scenarios, while the corner board is the same across all scenarios. In all cases the production of the banana box is the most significant source of emissions in the primary packaging.

Object	Weight (kg)	Material	Data Source
Box (NA - underdeck)	1.41	Cardboard	Chiquita specifications
Box (NA - container)	1.28	Cardboard	Chiquita specifications
Box (EU)	1.26	Cardboard	Chiquita specifications
Shroud (EU)	0.03	LDPE Plastic	Chiquita specifications
Shroud (NA)	0.03	HDPE Plastic	Chiquita specifications
Corner board	0.61	Cardboard	4 ft * 4 * .336 lbs/ft = 1.344 lbs per pallet load

Table 4.24: Packaging Data

Material	NA - Underdeck	NA - Container	EU
Banana Box	1.1	1.0	1.0
Plastic Shroud	0.1	0.1	0.1
Corner board	0.0	0.0	0.0
Total	1.2	1.1	1.1

Table 4.25: Emissions from Packaging Materials

4.3.5.2 Farm Chemicals

A number of agricultural chemicals are applied during banana cultivation, including fertilizers, pesticides, and fungicides. Exact chemical requirements vary by growing region and based on the specific qualities of the farms in question. Emissions related to the application of the chemicals were covered in the section on farm operations, while emissions of nitrous oxide due to application of nitrogen-based fertilizers are covered later in the section on other emissions sources.

Data Data regarding the chemicals used to help cultivate the bananas at the farm is based on recommended doses provided by CBI. Actual usage varies from farm to farm based on specific conditions and management. For fertilizers CBI's agricultural management group provided a list of recommended applications for eight chemicals in six divisions operating in different growing regions. The average value of the recommended dosage across all regions was used as the base scenario. The active ingredients recommended for use as fertilizers by CBI are nitrogen (N), phosphorus pentoxide (P_2O_5), potassium oxide (K_2O), magnesium oxide (MgO), boron (B), zinc (Zn), sulfur (S), and calcium oxide (CaO). In addition a recommended range of application quantities was provided for three more elements: iron

	Division					
Chemical	Cobigua	TRRCo	COBAL Sarapiqui	COBAL Matina Limon	BOFCo	Average
N	399	386	385	392	384	389.2
P_2O_5	88	85	92	92	83	88.0
K_2O	763	677	628	710	642	684.0
MgO	0	66	69	0	39	34.8
S	62	82	82	56	47	65.8
CaO	0	0	28	36	58	24.4
B	3.2	2.2	6.7	6.7	4.7	4.7
Zn	1.2	0.6	6.7	6.9	7	4.5
Fe	0-3	0-3	0-3	0-3	0-3	1.5
Cu	0-1	0-1	0-1	0-1	0-1	0.5
Mn	0-2	0-2	0-2	0-2	0-2	1.0

Table 4.26: Recommended Fertilizer Applications by Division (kg/ha/yr)

(Fe), copper (Cu), and manganese (Mn). The recommended application by division for each fertilizer is shown in Table 4.26.

In addition to fertilizers CBI provides a similar recommendation for the use of pesticides and fungicides. Recommendations are provided in the form of a range of the number of applications per year and the amount of active ingredient per application. The base scenario for analysis is based on using the midpoint of the recommended applications and amounts of active ingredients. The commercial name, active ingredients, and recommended annual applications are shown in Table 4.27.

All chemical usage is based on recommended doses per hectare per year. The amount of chemical usage per box was then calculated using farm yield data per hectare provided by CBI. Yield information is a key performance indicator for farm productivity, and CBI provided data on total average yield in boxes per hectare from different growing regions as shown in Table 4.28. Application of the chemicals is performed manually or by aerial spraying. It is assumed that no additional emissions arise from manual spraying, while emissions from aerial spraying are covered in the section on energy use at the farms. Emissions related to the delivery of chemicals to the farm are covered in the section on transportation.

Commercial Name	Active Ingredient	Amount (kg/ha/yr)
Opal 7.5 E.C	Epoxiconazole	0.2 - 0.3
Sico 25 EC	Difeconazole	0.3 - 0.4
Folicur 25 EW	Tebuconazole	0.3 - 0.4
Silvacur 30 EC	Tebuconazole y Tridiamenol	0.12 - 0.24
Tega 30C	Trifloxytrobin	0.1
Regnum 25 EC	Pyraclostrobin	0.1
Calxin 86OL	Tridemorph	2.15 - 4.30
Siganex 60 SC	Pyrimethanil	0.6 - 1.2
Impulse 80 EC	Spyroxamine	0.96
Dithane 60 SC	Mancozeb	57
Spraytex o Banole		27 - 432

Table 4.27: Recommended Pesticide Application (kg/ha/yr)

	Honduras and Guatemala	Costa Rica	Panama	Total
Hectares	5,000	6,400	5,000	16,400
Yield (boxes per ha)	2,550	2,400	2,400	2,446
Production (boxes)	12,750,000	15,360,000	12,000,000	40,110,000

Table 4.28: Farm Yield Data

Results The impact of chemical production under the baseline assumption for usage and average yield per hectare is shown in Table 4.29. Emissions from the application of nitrogen-based fertilizers are high due to the relatively high amounts applied as well as the intensity of the production process.

4.3.5.3 Other Materials

Data In addition to the primary packaging and chemical use at the farms, a limited number of other materials are used throughout the supply chain. This includes the ethylene used to chemically ripen the bananas at the ripening center, the plastic bottle the ethylene is packaged in, and a plastic banana bunch wrapper used to protect the banana bunches on the tree as they mature. Specifications for the plastic ethylene bottle and plastic banana wrap were not provided, instead estimates were created based on publicly available data for similar products:

- Banana Bunch Wrapper – 0.04 kg of LDPE plastic.

Chemical	Emissions
N	1.4
P_2O_5	0.0
K_2O	0.1
MgO	0.0
S	0.0
CaO	0.0
B	0.0
Zn	0.0
Fe	0.0
Cu	0.0
Mn	0.0
Pesticides	1.1
Total	2.6

Table 4.29: Emissions from Farm Chemical Production (kg CO_2e/box)

  - Source: `http://www.agnet.org/library/pt/2001036/`

- Ethylene Bottle - 0.06 kg of HDPE plastic.
  - Source: `http://www.thecompliancecenter.com/store/us/PK-P3200.html`

In addition to chemicals used to grow the bananas a small amount of ethylene fluid is used to chemically ripen the bananas just before sale. One 32 ounce bottle of ethylene fluid is composed almost entirely of ethanol and is capable of ripening a full container (960 boxes) of bananas. The fluid is used in specially designed banana ripening rooms that catalyze the ethanol and release the ethylene as a gas to circulate it among the banana boxes. This process causes the bananas to ripen over a period of three to four days, at which point they are ready to sell.

Results As shown in Table 4.30 none of these materials produce significant emissions relative to the overall supply chain. The effect of allocating emissions from the ethylene over an entire container load of bananas reduces the overall impact of producing both the ethanol and the plastic bottle.

Material	Emissions
Ethylene Bottle	0.0
Ethylene Fluid	0.0
Banana Wrapper	0.1
Total	0.1

Table 4.30: Emissions from Other Materials (kg CO_2e/box)

4.3.6 Other Emissions

Two other sources of emissions included in this study are the release of certain refrigerant gases to the atmosphere and the release of nitrous oxide due to the application of nitrogen-based fertilizers to soil. Land use changes can also contribute to climate change; however, they are excluded from this study as the farms that produce bananas are generally pre-existing and not the result of recent changes in land use.

Nitrous oxide is produced naturally in soil, and one of the main factors in its production is the amount of nitrogen in the soil. When nitrogen is added to the soil through the application of fertilizers the amount of available nitrogen increases, resulting in increased production of N_2O. N_2O is a greenhouse gas with a GWP of 298, meaning each kg of N_2O in the atmosphere produces a warming effect equivalent to 298 kg of CO_2. Given its high global warming potential and the use of nitrogen-based fertilizers at the banana farm an estimate of the impact from nitrous oxide production is included in this study.

Many of the chemicals used in the refrigeration process are also powerful greenhouse gases. Over the course of time some of these gases escape from the refrigeration equipment into the air and contribute to climate change. Since bananas are generally kept in a cooled environment from the time they are packed at the farm until they arrive at the retail store, the loss of refrigerant gases to the atmosphere can produce significant emissions.

4.3.6.1 Nitrous Oxide

Data The amount of N_2O produced is calculated based on IPCC recommendations of 1% of nitrogen applied as fertilizer being converted to N_2O (IPCC, 2006). The ratio of mass of N_2O to N is 44:28, thus for every 100 kg of N applied as fertilizer 1 kg will be converted to N_2O producing about 1.57 kg N_2O. The amount of N_2O produced is therefore tied to the amount

	Amount
Nitrogen (kg/ha)	389
N_2O Emissions (kg/ha)	6.1
GWP	298
Yield (boxes/ha)	2446
CO_2e (kg/box)	0.8

Table 4.31: Emissions from Nitrous Oxide (kg CO_2e/box)

of nitrogen fertilizer applied, and all emissions are derived from the data for application of fertilizers at the farms. Emissions from the N_2O production are then allocated based on the average yield per hectare provided by CBI in Table 4.28.

Results The production of nitrous oxide in soil due to application of nitrogen fertilizers leads to 0.8 kg of CO_2e per box. When combined with the emissions due to production of the fertilizer, this makes the use of nitrogen fertilizers a significant source of emissions in the context of the total carbon footprint.

4.3.6.2 Refrigerant Emissions

Data Data regarding loss of refrigerant gases is based on purchases of gases used to recharge refrigeration equipment during maintenance. It is assumed that the level of gases contained in the tanks is maintained at a consistent level, and therefore any added gases are to replace gases that have escaped to the atmosphere. This 100% fugitive rate assumes that none of the refrigerants are captured during the recharging process and represents an upper range of possible emissions.

North America Data for consumption of refrigerants was supplied for all five ports and two DCs. This data consisted of the total kilograms of each type of refrigerant added to the cooling system during maintenance for the year. For some locations sealed refrigerating equipment is used, and so no data on refrigerant recharges was available. Instead the total refrigerant charge capacity was supplied and an annual leakage rate of 2% was assumed based on guidelines supplied by the Green Building Council (Rubenstein, Didion, and Dozier, 2004). Refrigerant quantities based on estimated leakage rates are noted with an asterisk in

Location	Boxes	R-134A	R-12	R-409A	R-22	R-123
Wilmington	23,319,318	694	125	411	0	0
Gulfport	14,449,053	240	120	210	0	0
Port Everglades	7,352,312	67	6	22	0	0
Hueneme	14,087,360	0	0	0	0	60*
Freeport	3,957,968	29	38	17	0	0
Total	63,166,010	1,030	289	660	0	60

Table 4.32: Refrigerant Usage in North American Ports (kg)

Location	Boxes	R-134A	R-12	R-409A	R-22	R-123
Mid Atlantic	2,439,871	0	0	0	300*	0
Los Angeles	2,922,417	0	0	0	250	0
Total	5,362,288	0	0	0	550	0

Table 4.33: Refrigerant Usage in North American DCs (kg)

Table 4.32 and Table 4.33. Average refrigerant leakage per box was calculated separately for ports and DCs based on total refrigerant usage and boxes processed at each stage.

Europe No data was provided regarding refrigerant use in Europe. Consumption has been assumed to be identical to that of North America for this report.

Tropics The provided data for the tropics shows the total amounts, in tonnes, of four refrigerant gases: R-134a, R-12, R-409a, and foam froth. Based on the quantities and GWP of the gases, R-134a and R-12 combine to produce more than 95% of the greenhouse gas emissions. Data regarding the refrigerant usage was provided in total for one growing region, and the emissions were allocated on a per box basis to the total number of boxes produced in that growing region during the time period. This data is summarized in Table 4.34. The total refrigerant usage per box, including both origin and destination operations, is shown in Table 4.35.

Refrigerant	Amount (tonnes)	GWP	CO_2e (tonnes)	Production (Boxes)	Amount Per Box (g/box)	CO_2e Per Box (kg CO_2e/box)	Share of CO_2e
R-134a	1.66	1430	2155.10	12,121,430	0.14	0.2	24%
R-12	0.66	10900	4654.12	12,121,430	0.05	0.6	72%
R-409a	0.29	1548.75	376.78	12,121,430	0.02	0.0	5%
Foam Froth	0.02	286	4.81	12,121,430	0.00	0.0	0%

Table 4.34: Refrigerant Data, Tropics

	R-134a	R-12	R-409a	Foam Froth	R-22	R-123
GWP	1430	10900	1584.75	286	1700	76
Tropics (g/box)	0.137	0.054	0.024	0.002	0.000	0.000
Destination Port (g/box)	0.016	0.005	0.010	0.000	0.000	0.001
Destination DC (g/box)	0.000	0.000	0.000	0.000	0.103	0.000
Total (g/box)	0.153	0.059	0.034	0.002	0.103	0.001
CO_2e (kg/box)	0.219	0.639	0.054	0.000	0.174	0.000

Table 4.35: Refrigerant Data Per Box

Process	Emissions
Refrigerant Production	0.0
Refrigerant Leakage	1.1
Total	1.2

Table 4.36: Emissions from Refrigerants (kg CO_2e/box)

Results The emissions from the production and leakage of refrigerants are shown in Table 4.36. The emissions from the production of the refrigerant are low relative to the effects of its release to air due to the high global warming potential of the refrigerants.

4.3.6.3 End of Life

Disposal of all packaging materials used are considered within the system boundary for the banana carbon footprint. This includes the ethylene bottle, plastic shroud, cardboard corner board, and the banana box.

Data According to interviews with Shaw's, the typical practice at their stores is for all cardboard materials to be collected and sent to a recycler. Plastics are generally thrown out and disposed of by the waste collection service. As this practice may not be representative of all customers, an average waste disposal scenario was applied and a sensitivity analysis was performed to estimate the impact of disposal practices. Emissions for the disposal of packaging materials are allocated to the bananas in the same manner as emissions from the production of the materials.

Results Emissions from the disposal of packaging materials are shown in Table 4.37. Similar to production of the packaging, emissions from disposal are driven almost entirely by

Material	NA - Underdeck	NA - Container	Europe
Banana Box	1.0	0.9	0.5
Plastic Shroud	0.0	0.0	0.0
Banana Wrapper	0.0	0.0	0.0
Corner Board	0.0	0.0	0.0
Ethylene Bottle	0.0	0.0	0.0
Total	1.0	0.9	0.5

Table 4.37: Emissions from Packaging Disposal (kg CO_2e/box)

the cardboard banana box.

4.4 Results

The end result of this project was an estimated carbon footprint of approximately 17 kg of CO_2e per banana box in North America and 23 kg of CO_2e per banana box in Europe. When calculated for the secondary functional unit this results in approximately 1.0 kg of CO_2e per kg of sold bananas in North America and 1.3 kg of CO_2e in Europe. All numbers are based on an average scenario for each market consisting of:

- Standard EU packaging for Europe and the NA container packaging for North America.
- Identical farming scenarios consisting of average chemical usage and yield per hectare.
- Average transportation distance from the farm to the port calculated separately for bananas destined for North America and Europe.
- Identical operations at the origin port in the tropics.
- Average ocean distances based on shipping distances of each service to the destination ports.
- Average ground shipping distances at the destination market.
- Average facility energy consumption for all ports, DCs, and stores within the destination market.

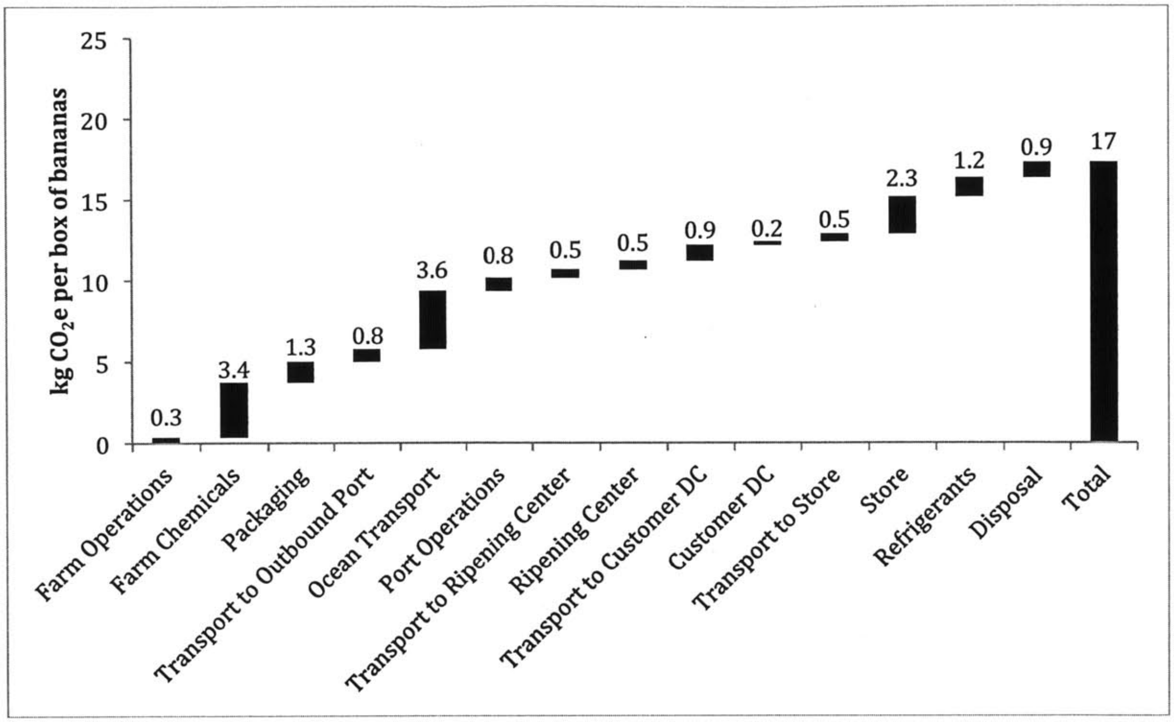


Figure 4-2: Carbon Footprint Breakdown (North America)

- US packaging waste scenario for North America and the England packaging waste scenario for Europe.

A breakdown of the carbon footprint for North America is shown in Figure 4-2 and for Europe in Figure 4-3. In a comparison between the two markets the increased ocean shipping distance tends to dominate the comparison, producing more than three times as much CO_2e in the European scenario than in the North American case. This is only slightly offset by the generally lower emissions from transportation and facility operation due to shorter travel distances, lower energy consumption, and lower emissions intensity of electricity in Europe.

4.4.1 By Activity

Rather than view the emissions by where they occur in the supply chain, it is also useful to see the types of activities that generate the most emissions. In this breakdown the emissions are separated into the following categories:

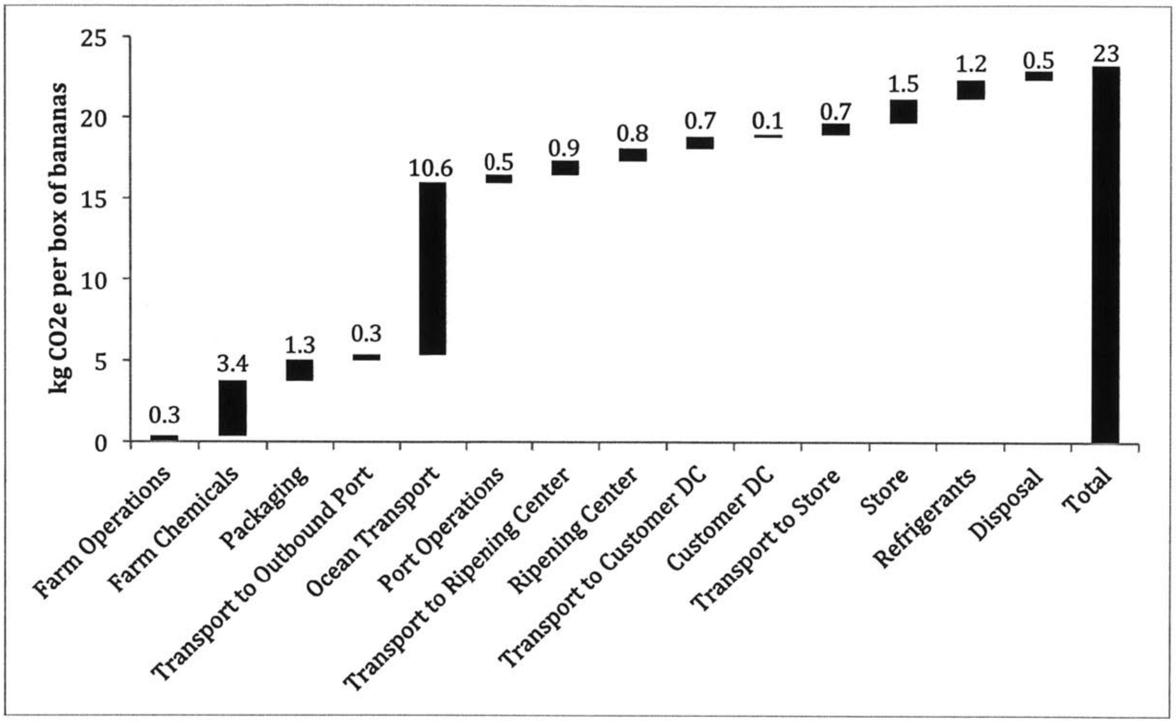


Figure 4-3: Carbon Footprint Breakdown (Europe)

- Transportation—includes all ground and ocean transportation from the time the bananas leave the farm until they arrive at the store.
  - Also included are emissions from running the refrigeration equipment needed to keep the bananas cool during transit.
- Distribution Facilities—All emissions from facilities operated in the distribution channel; including ports, distribution centers, and retail outlets.
- Production—All emissions related to growing and packing the bananas; including emissions due to chemical production, chemical spraying, and nitrous oxide.
- Packaging—All emissions from the production and disposal of packaging materials.
- Refrigerants—All emissions from producing refrigerants and the fugitive emissions from their release during operation.

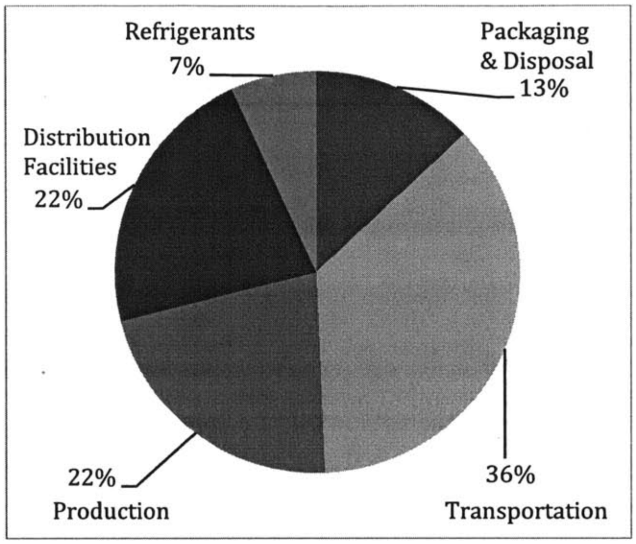
Stage	North America	Europe
Farm to Port	0.8	0.3
Port to DC	0.5	0.9
DC to Customer	0.9	0.7
Customer DC to Store	0.5	0.7
Ocean	3.6	10.6
Total	6.3	13.2

Table 4.38: Emissions from Transportation (kg CO_2e/box)

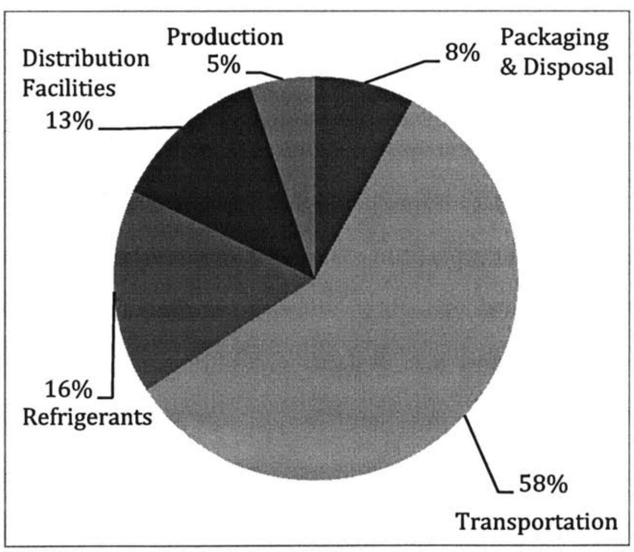
Figure 4-4 shows the respective distribution of emissions for both the North American and European markets for these categories.

4.4.1.1 Transportation

Transportation as a whole represents the largest share of supply chain emissions, and the single largest source in each case is due to ocean shipping. For Europe the ocean voyage is responsible for 46% of the total carbon footprint, while it is 21% of emissions for North America. If changes in ocean shipping operations could produce efficiencies similar to the standard Ecoinvent assumptions for transoceanic freight this would produce a large reduction in emissions, reducing the total carbon footprint to about 15 kg per box in Europe and 14 kg in North America. The higher emissions of CBI's ocean operations is attributable to a number of factors, including smaller vessels, lower utilization on the backhaul, and higher sailing speeds. According to data supplied by CBI, cargo on the backhaul portion of the voyage represents only 22% of total tonnes shipped, and can be as low as 7% for certain rotations. The need to get bananas to market as quickly as possible in order to maintain quality and freshness results in higher emissions due to the relationship between vessel speed and fuel consumption. Cariou (2011) estimates that larger container ships sailing 30% slower can reduce fuel consumption by 55%. Thus, if possible, a combination of reducing sailing speed and increased backhaul utilization could significantly reduce the impact of the ocean shipment.



(a) North America



(b) Europe

Figure 4-4: Comparison of Carbon Footprint by Category

Source	North America	Europe
Fertilizer, N	1.4	1.4
Fertilizers, Other	0.2	0.2
N_2O	0.8	0.8
Pesticides	1.1	1.1
Packing	0.1	0.1
Fertilizer Spraying	0.2	0.2
Total	3.8	3.8

Table 4.39: Emissions from Production (kg CO_2e/box)

4.4.1.2 Production

Emissions related to producing bananas are primarily driven by the use of fertilizers, and in particular nitrogen-based fertilizers. The emissions from operating the packing stations and powering the farms represent only 5% of the total emissions related to production. The remaining 95% are due to production of fertilizers, N_2O emissions, and aerial spraying of the chemicals. Production of nitrogen fertilizer accounts for 2.2 kg of the total 3.8 kg when emissions from its production and related N_2O are accounted for.

4.4.1.3 Packaging

Emissions from production and disposal of packaging materials accounts for 8% of the total carbon footprint in Europe and 12% in North America. This is driven almost entirely by the production and disposal of the cardboard box, which represents more than 90% of the total emissions from all packaging materials. The higher rates of recycling in the European scenario result in lower emissions from disposal than in North America.

4.4.1.4 Distribution Facilities

The single largest source of emissions among distribution facilities is the retail store. Though total emissions from the store are generally lower than in the various distribution centers, the lower level of efficiency per unit of product leads to higher emissions.

Material	Stage	North America	Europe
Banana Box	Production	1.0	1.0
Banana Box	Disposal	0.9	0.5
Plastic Shroud	Production	0.1	0.1
Plastic Shroud	Disposal	0.0	0.0
Banana Wrapper	Production	0.1	0.1
Banana Wrapper	Disposal	0.0	0.0
Corner Board	Production	0.0	0.0
Corner Board	Disposal	0.0	0.0
Ethylene Bottle	Production	0.0	0.0
Ethylene Bottle	Disposal	0.0	0.0
Total		2.2	1.8

Table 4.40: Emissions from Packaging Materials (kg CO_2e/box)

Facility	North America	Europe
Port, Tropics	0.3	0.3
Port, Destination	0.5	0.2
CBI DC	0.5	0.8
Customer DC	0.2	0.1
Retail Store	2.3	1.5
Total	3.8	2.9

Table 4.41: Emissions from Distribution Facilities (kg CO_2e/box)

4.4.1.5 Refrigerants

The production and escape of refrigerant gases combine to produce 5% of the total emissions in Europe and 7% in North America. The results may be surprising given the small amounts of refrigerants involved–less than one gram per box–but the high GWP of some of the gases produces large amounts of CO_2e.

4.5 Conclusions

In this chapter we presented an LCA of the banana supply chain used to measure the carbon footprint. Our results show the carbon footprint of a box of bananas to be approximately 17 kg of CO_2e for bananas sold in North America and 23 kg of CO_2e for boxes sold in Europe. We identified 1 kg of sold bananas as a secondary functional unit, with a carbon footprint of about 1.0 kg of CO_2e in North America and 1.3 kg of CO_2e in Europe. The primary source of emissions in the supply was found to be transportation, with the ocean voyage having the single largest impact. The second largest impact was from production of the bananas at the farm, and this was primarily related to the use of chemicals during cultivation.

Despite the visibility to a significant portion of the supply chain allowed by the participation of both CBI and Shaw's, a significant amount of uncertainty exists in the results of this study. In the next chapter we examine some of the specific sources of uncertainty and quantify their impact on the measured carbon footprint. We then propose a solution for improving the results of supply chain carbon footprint measurements.

Chapter 5

The Carbon Label Framework

In the previous chapter we presented the use of Life Cycle Assessment as a method of measuring the carbon footprint of a supply chain through a case study of banana production. While the end result of the study is a measure of the carbon footprint of a case of bananas, the measurement contains a great deal of uncertainty due to the complexities of performing an LCA across an entire supply chain. In this chapter we discuss the sources of uncertainty in an LCA, demonstrate their applicability to our case through a sensitivity analysis, and finally present a framework based on the idea of a carbon label as a way to facilitate cooperation in the supply chain to reduce uncertainty in the carbon footprint measurement.

5.1 Uncertainty in LCA Results

Issues with data quality and uncertainty in LCA are well known, and several authors have provided reviews of the issues (Reap, Roman, Duncan, and Bras, 2008; Bjorklund, 2002; Ross, Evans, and Webber, 2002; Huijbregts et al., 2001; Heijungs and Huijbregts, 2004; Coulon, Camobreco, Teulon, and Besnainou, 1997; Bretz, 1998). LCA results are usually presented as point estimates, which strongly overestimates their reliability (Bjorklund, 2002). In a review of approaches to improve the reliability of LCA, Bjorklund (2002) distinguished between uncertainty and variability. Uncertainty occurs due to lack of knowledge about the true value of a quantity, while variability is due to natural heterogeneity of values. Within these categories a number of specific types and sources of uncertainty can be identified,

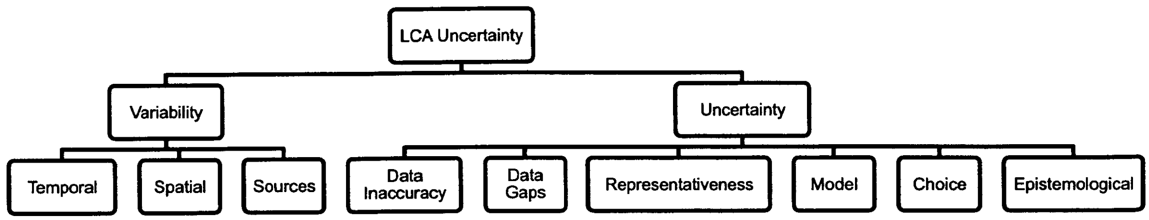


Figure 5-1: Sources of Uncertainty (Bjorklund, 2002)

shown in Figure 5-1.

Sensitivity analysis is one of two main classes of techniques used in LCA to evaluate uncertainty. It involves studying the effects of changes to inputs on the LCA results, and it is useful to identify the most influential inputs when their uncertainty has not or cannot be quantified (Reap et al., 2008). We conducted a number of sensitivity analysis scenarios to identify areas with considerable uncertainty or variability in the banana supply chain. Individual factors were varied one at a time between their minimum and maximum values and the resulting changes in the carbon footprint were calculated. Table 5.1 contains a summary of the impact of these scenarios. In each case the carbon footprint value was compared to the base scenario of 17.2 kg CO_2e for North America and 23.2 kg for Europe. Several areas of high uncertainty were identified through scenario analysis and the initial data reliability assessment. The uncertainty is primarily related to the production of bananas, transportation distances, customer operations, and final disposal of packaging.

The largest single cause of uncertainty in Europe is the ocean voyage. Differences in efficiency and shipping distances on the shipping rotations lead to variability within the results. Given the large overall impact of the ocean voyage this variability creates the greatest uncertainty in the overall results. In North America, with longer road distances and shorter ocean voyages, the greatest source of uncertainty is the road transportation distance. This is primarily a result of the significant extra distance required to reach DCs located in the central regions of the United States when compared to DCs located on the coast, or in Europe where the greater number of inbound ports and smaller geographic region leads to

	North America				Europe			
	Min		Max		Min		Max	
Sensitivity Parameter	kg CO_2e	% Decrease	kg CO_2e	% Increase	kg CO_2e	% Decrease	kg CO_2e	% Increase
Chemical Quantity	16.3	5%	19.9	16%	22.2	4%	25.8	12%
Fertilizer Emissions Factor	16.2	6%	18.4	7%	22.2	4%	24.4	5%
Pesticide Emissions Factor	16.4	5%	19.2	12%	22.3	3%	25.1	9%
Packing Operations	17.2	0%	17.4	1%	23.1	0%	23.3	1%
Ocean Factor	14.4	16%	17.2	0%	14.6	37%	23.1	0%
Ocean Distance	15.3	11%	19.0	10%	21.8	6%	25.9	12%
Port to DC Distance	16.4	5%	22.0	28%	23.0	0%	23.3	1%
DC to Customer Distance	16.8	2%	17.7	3%	22.4	3%	24.0	4%
Customer DC to Store Distance	16.7	3%	18.2	6%	22.7	2%	24.7	7%
Origin Port Operations	17.2	0%	17.7	3%	23.1	0%	23.6	2%
Destination Port Operations	17.0	1%	17.6	3%	22.1	4%	24.8	7%
Chiquita DC Operations	17.0	1%	17.5	2%	22.5	3%	24.9	8%
Waste Scenario	16.3	5%	18.6	8%	22.6	2%	24.9	8%

Table 5.1: Sensitivity Analysis Results

shorter road shipping distances.

The production of bananas represents another source of uncertainty within CBI's supply chain. Production is uncertain due to the wide range of types and quantities of chemicals that may be applied during cultivation and differences in farming practices. Bananas are sourced from hundreds of farms located in several different regions, making full data collection difficult in practice. In the future more data on actual chemical usage and farming practices in the different growing regions will be necessary to help reduce this uncertainty.

The other areas of uncertainty are related primarily to the lack of knowledge regarding the exact processes used by upstream and downstream portions of the supply chain. The packaging poses a special challenge to CBI, as all of its emissions occur either upstream during production or downstream in disposal. This makes evaluating changes to the packaging process difficult, as in the case of one current customer that uses returnable plastic containers instead of cardboard boxes for storage. A similar problem with evaluating downstream emissions occurs with customer operations at the retail level. Through the cooperation of Shaw's, an estimate of the impact of the retail stage was included, but the uncertainty surrounding customer operations is high due to the large impact of the retail store and the lack of representative data for many retail customers.

In addition to the sensitivity analysis based on the amount of chemicals applied, a second analysis was performed in SimaPro based on the types of chemicals used. The production of pesticides, fungicides, and nitrogen based fertilizers represent 90% of the total emissions from chemical production. No other fertilizer or chemical contributes more than 5% to the total. To test the sensitivity to the assumptions regarding these chemicals the emissions from the base scenario were compared with a range of other available chemical choices.

While the recommended quantity of nitrogen fertilizer is known, the exact choice of fertilizer is not. In the base scenario ammonium nitrate was assumed, but in order to test the sensitivity of the results to that assumption the emissions from this choice were compared to the other available nitrogen-based fertilizers. The emissions from production of ammonium nitrate are 1.4 kg of CO_2e per box and are represented by the horizontal line in Figure 5-2. Only one other fertilizer, potassium nitrate, produces significantly higher emissions than ammonium nitrate. The use of potassium nitrate would increase the total

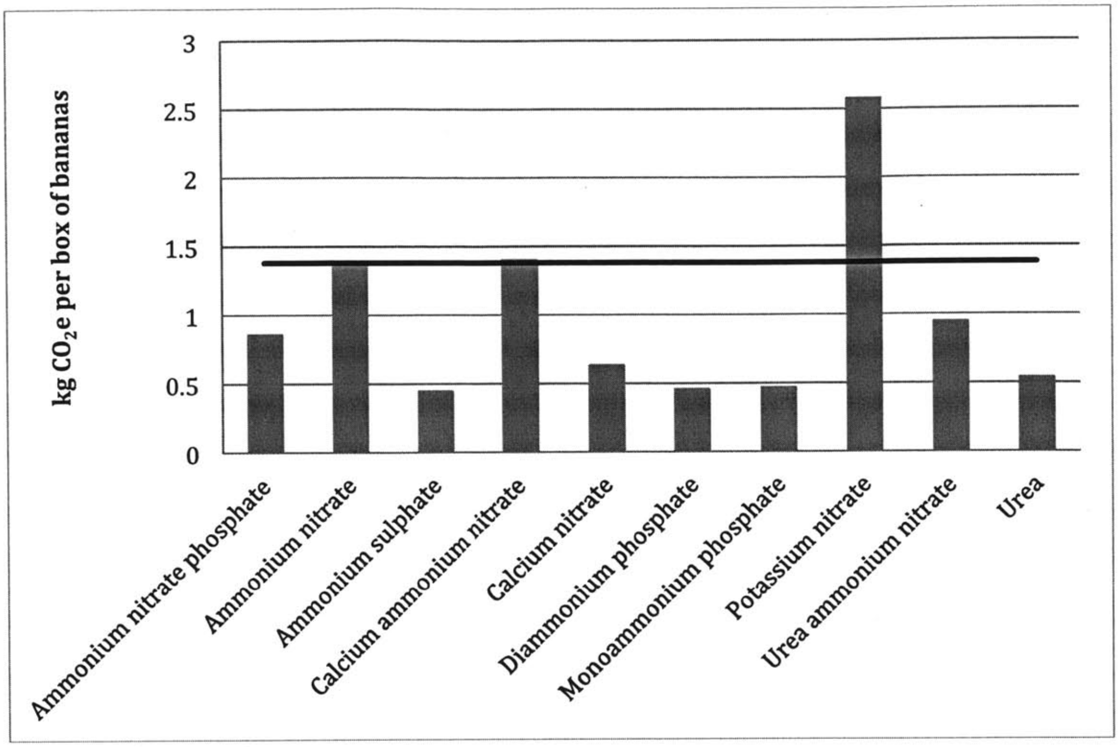


Figure 5-2: Comparison of Ecoinvent Nitrogen Fertilizer Production Processes

carbon footprint by 7% in the North American case and 5% in the European case. The use of the mean value of nitrogen fertilizer production would result in a 2% reduction in the total carbon footprint for both North America and Europe, while the median would decrease the carbon footprint by 4% in North America and 3% in Europe.

Not all chemicals have LCA data available in the Ecoinvent database, and in the case of those used in banana cultivation none of the specific pesticides or fungicides have data available. The base scenario used the Ecoinvent process for an unspecified pesticide, which produced 1.06 kg of CO_2e per box. To estimate the range of possible values for the emissions from pesticide production, the emissions per kg for all thirty-seven chemicals available in the Ecoinvent pesticide database were calculated. Figure 5-3 shows the results when these values are used in place of the value for unspecified pesticides on a per box basis. Each vertical bar represents the emissions related to production of a specific chemical, while the horizontal bar provides a comparison with the level of emissions for the base scenario. In the case of the mean and median values from the sample of thirty-seven chemicals the effect on the total

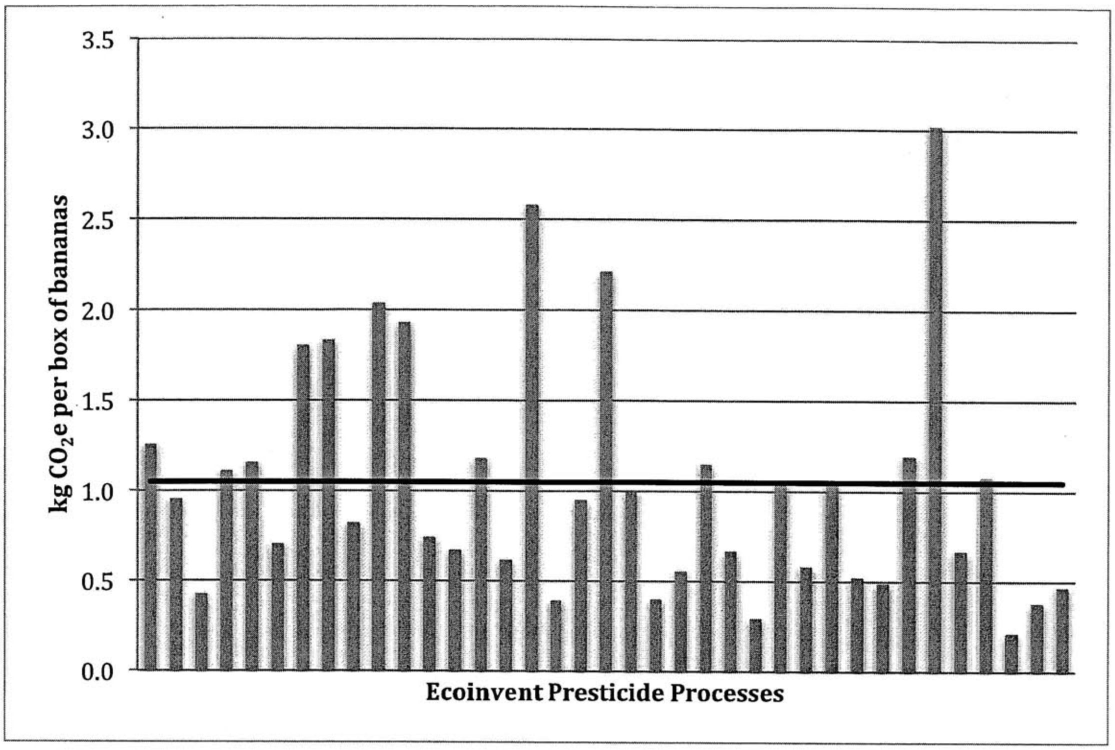


Figure 5-3: Comparison of Ecoinvent Pesticide Production Processes

carbon footprint for both the North American and European scenarios is a reduction of less than 1%. Using the minimum and maximum values from the sample produces a decrease of 5% and an increase of 11%, respectively, for North America. This corresponds to a 4% reduction and an 8% increase for the European case.

We consider both uncertainty and variability to be important issues related to this study. In order to explore this further we analyzed their role in the context of this study in two ways. First, in Section 5.1.1 we consider uncertainty by analyzing the upstream and downstream sources of emissions within the context of scopes identified by the GHG Protocol. Second, in Section 5.1.2 we consider the variability aspect through an analysis of differences in the distribution of bananas to various customers, and the role that transportation plays in the calculated carbon footprint.

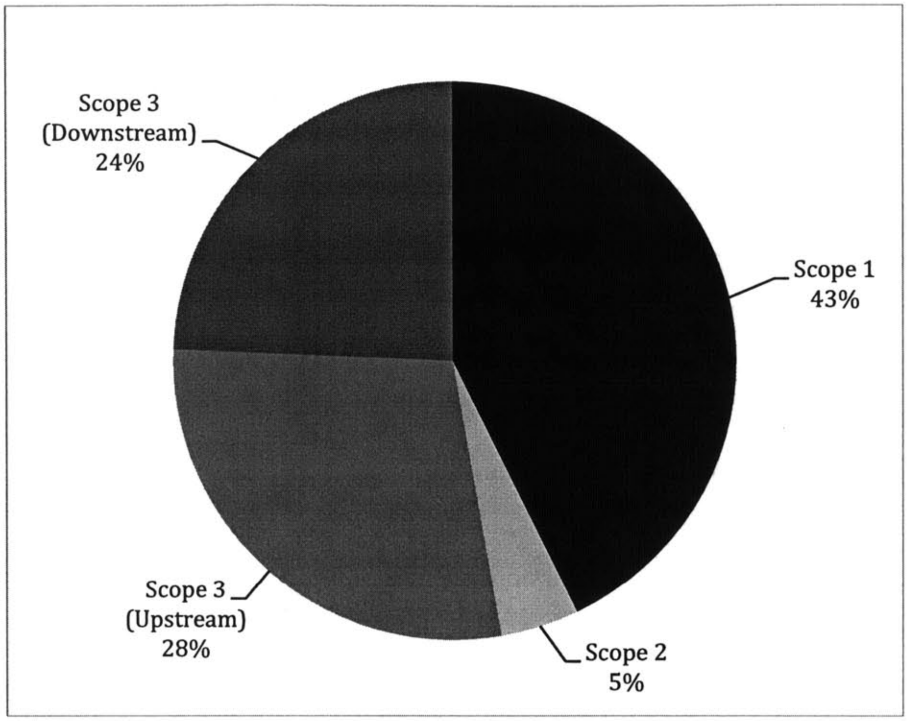


Figure 5-4: Share of Emissions by Scope

5.1.1 GHG Protocol Scopes

Two previous studies have attempted to estimate which life cycle emissions fall under various GHG Protocol scopes. Using an input-output analysis for all 491 sectors of the U.S. economy, Matthews et al. (2008) found that for the average sector only 14% of emissions are scope 1 and 12% are scope 2. Huang et al. (2009) also apply the EIO-LCA method to estimate the upstream scope 3 emissions for a variety of industry sectors as a percentage of total emissions. Their results show that the share of upstream scope 3 emissions usually falls in the 70-80% range, but can be as little as about 5% in industries such as power generation. Applying a similar concept to the results of this study, but also including the downstream portion of the supply chain, we classify the share of emissions of each scope for CBI as shown in Figure 5-4.

We consider scope 1 emissions to be all those that occur due to fuel combustion, refrigerant leakage, and N_2O emissions at CBI facilities or in CBI controlled transportation. The facilities include farms, packing stations, port facilities, and ripening centers. CBI controlled transportation consists of the farm to port, ocean transport, port to DC, and DC to customer DC legs. Scope 2 emissions account for all electricity usage at farms, packing stations, ports, and DCs. Scope 3 emissions include chemical production, packaging production and disposal, fuel consumption during aerial spraying, upstream production of fuels for scope 1 and scope 2 activities, and all downstream activities associated with the retailer beginning with product arrival at the customer DC. This represents a broad definition of scope 1 emissions, as in practice some transportation legs may be handled by third party carriers which would be considered scope 3. However, since the actual ownership will vary by shipment we choose to account for them as scope 1 in this analysis.

From this data we can see that more than half of the emissions occur as scope 3 emissions. The remaining scope 1 and scope 2 emissions, which would be those considered within CBI's corporate carbon footprint, account for 43% and 5%, respectively. The results highlight the difficulties in performing a full carbon footprint for a supply chain. Despite high levels of visibility and control of the supply chain a large portion of the emissions occur outside of CBI's control, both upstream and downstream in the supply chain. As discussed in Chapter 3, neither of the generally used approaches to fill in data gaps–either the use of EIO-LCA data or LCI process databases–are without issues. The accessibility of data is considered a serious issue in LCA (Bretz, 1998), and the lack of representative data may result in unreliable results (Huijbregts et al., 2001). One possible method for improving the data quality in carbon footprinting is to collect specific process-based data directly from suppliers.

Both the GHG Protocol and Carbon Trust have proposed using a business-to-business (B2B) sharing arrangement to provide information to supply chain partners. The Carbon Trust carbon label program certified more than £2 billion in consumer products and £1 in business-to-business products (Carbon Trust Certification Limited, 2011). On a B2B labeled product the carbon footprint boundary stops when the product arrives at the customer's door, and downstream emissions are excluded. In LCA this is referred to as a cradle-to-gate analysis, as it does not cover the full cradle-to-grave life cycle of the product. This is intended to facilitate the sharing of information in the supply chain. By providing the cradle-to-gate carbon footprint to downstream customers, incremental additions to the carbon footprint can be added at each stage of the supply chain until sale to the end consumer (BSI, 2011). If the producer of the final product to the end consumer then accounts for the use and end-of-life phases this approach can cover the entire life cycle of the product. The GHG Protocol Scope 3 standard explicitly allows for use of supplier data in both the value chain and product standards (WRI and WBCSD, 2011b,a). The use of actual supplier data has several benefits, including increased transparency, better reflection of changes in emissions due to efforts to reduce emissions, and more effective tracking and reporting of GHG reduction goals (WRI and WBCSD, 2011b). In their analysis of upstream emissions Huang et al. (2009) showed that firms can capture a significant portion of their upstream emissions by collecting data from only a limited number of direct suppliers. While sharing carbon footprint information with downstream supply chain customers has the possibility to improve the results of a supply chain carbon footprint measurement, it poses a challenge related to variability within the supply chain.

5.1.2 Supply Chain Variability

If carbon footprint data is to be shared between supply chain partners it is important to understand how variability in the supply chain affects the carbon footprint. Sundarakani, De Souza, Goh, Wagner, and Manikandan (2010) noted this need to study carbon footprint measurement across supply chains for a better understanding of the impact in the context of global supply chains. The importance of variability within the system has been identified in both the supply chain and LCA literature on carbon footprinting. McKinnon (2010) identifies variability within the supply chain as one of the problems with trying to calculate product level carbon footprints. Bjorklund (2002) identifies several types of variability within LCA, including variability between sources, which may arise due to differences in processes. The aggregation of emissions in the inventory analysis of an LCA can cause the loss of certain variability characteristics (Huijbregts, 1998). Including these uncertainties in the results of an LCA have been recognized as an important factor in improving the use of LCA as a decision making tool (Heijungs and Huijbregts, 2004). If customers plan to use the carbon footprint information shared by suppliers in their sourcing decisions then this variability must be accounted for in the measurement. Roos, Sundberg, and Hansson (2010) noted that the spatial and temporal uncertainties, including differences in distribution, make measuring the carbon footprint of a food product particularly complex.

To address this issue we consider the variability within the banana supply chain through an analysis of the role of transportation required to deliver the product to specific customers in the United States. Previous work has shown that a focus on food delivery miles is generally less important in reducing emissions than food choice (Weber and Matthews, 2008). Thus, a focus solely on the emissions from transportation is shortsighted. However, given the high impact of transportation in the supply chain for bananas, delivery distance can represent a key area of variability in the carbon footprint. The variability is introduced in two ways. First, the bananas are brought to the U.S. on one of three ocean services: dedicated service to the West Coast, dedicated service to Port Everglades, and a combined service that alternates between Wilmington and the Gulf Coast. Each service achieves different levels of efficiency due to differences in average shipment size, backhaul utilization, and distance traveled. Once bananas reach port in the United States the second level of variability is introduced, as the bananas must be distributed to customers located throughout the country. To do so the bananas move through a distribution network that includes the five destination ports, ten ripening centers, and finally on to more than 250 retail customer locations. A map showing the locations of the various facilities is shown in Figure 5-5.

Each of the three ocean rotations operated by Chiquita provides a different level of efficiency. The Wilmington-Gulfport-Freeport service works on a rotation that visits Wilmington, returns to the tropics, visits Gulfport and Freeport, and then returns to the tropics before beginning again. The West Coast and Port Everglades services each call on only one port in the U.S. before returning to the tropics to complete the rotation. As the ocean voyage represents the single largest aspect of the carbon footprint, the variability between the different shipping rotations, due to both distance and relative efficiency, has a significant impact on the calculated carbon footprint. A summary of data related to the different services is shown in Table 5.2. The differences in service efficiency and distances create a range of emissions required to serve each port ranging from 2.2 kg of CO_2e per box at Gulfport to 6.7 kg for service to the West Coast. This represents a considerable variation from the 3.6 kg of CO_2e per box average.

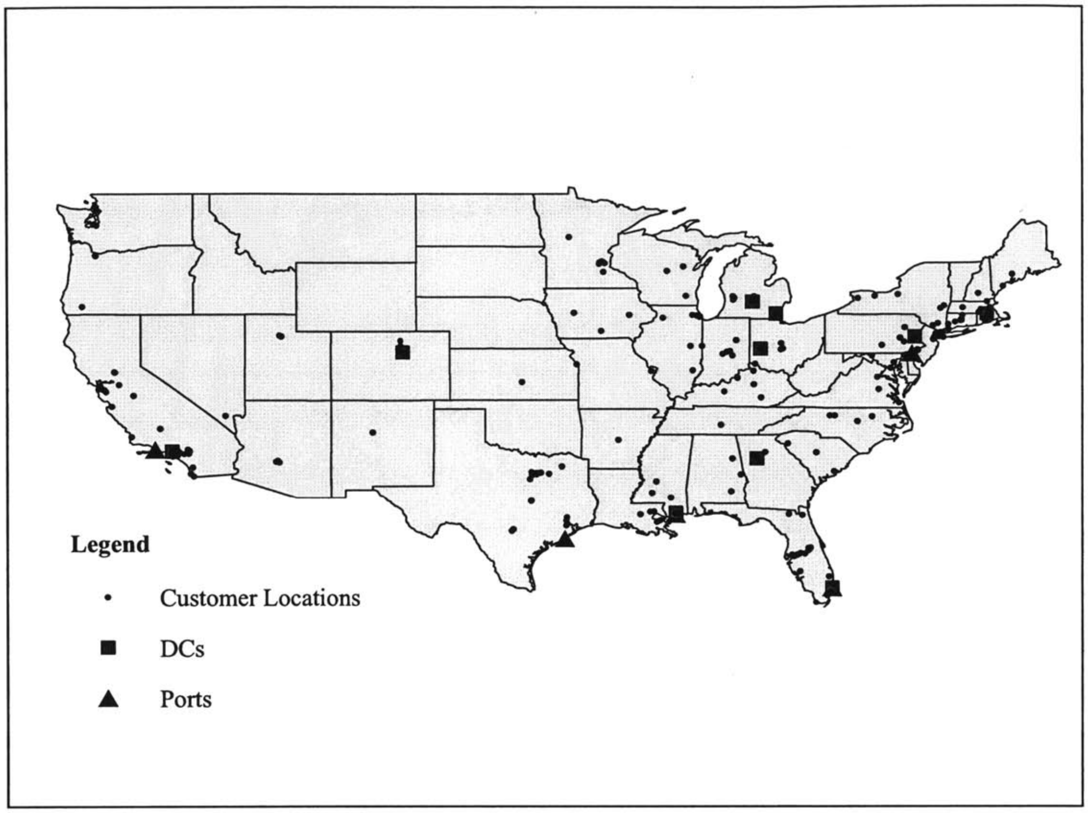


Figure 5-5: Map of Facility Locations

Service	Fuel Consumption (tonnes)	Cargo (tkm)	Fuel Efficiency (g/tkm)	% Backhaul
Wilmington-Gulfport-Freeport	1,054	100,521,756	10.5	34%
Port Everglades	360	35,390,431	10.2	15%
West Coast	1,443	89,586,805	16.1	7%
All	2,857	225,498,992	12.7	28%

Table 5.2: Fuel Efficiency by Service

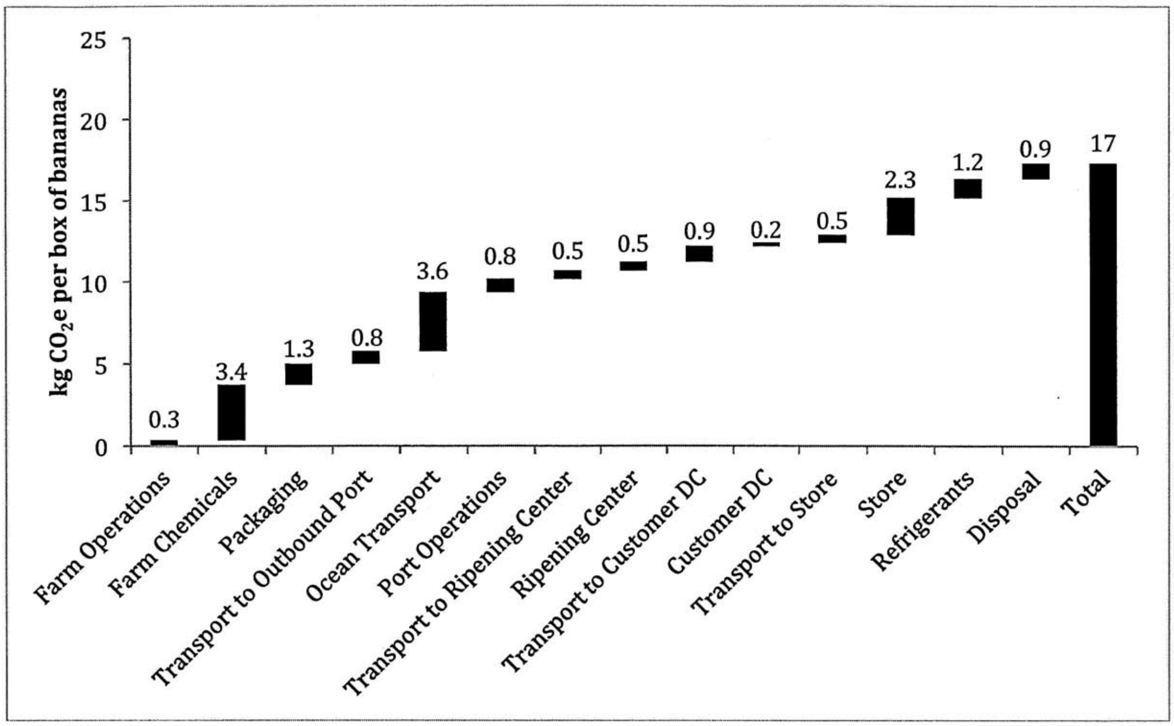


Figure 5-6: Carbon Footprint Breakdown (North America)

Though emissions from distribution within the United States are on average lower than the ocean voyage they involve a considerably higher amount of variability. Some customers, such as those located near the inbound ports and DCs, require a negligible amount of trucking, while others requires thousands of miles of travel to receive delivery. When combined with the variability required to reach the port, this results in a range of values for the carbon footprint of a box of bananas delivered to different customers, variability that is not captured through the use of average carbon footprint values. To illustrate this variability we have calculated the carbon footprint for each customer location that CBI delivers products to. The carbon footprint consists of all emissions up to delivery at the customer's DC, as well as the estimated emissions from the disposal of packaging material. We refer to this as the B2B carbon footprint, as calculated in this manner the retail customer would be able to calculate the emissions of their own operations and add them to the value supplied by CBI to get a total carbon footprint. This ability to do incremental additions is at the core of the business-to-business label idea used by the Carbon Trust.

The average B2B carbon footprint calculated in this manner is 14 kg CO_2e per box

Count	254	Coefficient of Variation	0.10
Mean	13.8	Mean Deviation	1.09
Standard Deviation	1.38	Median	13.3
Minimum	11.5	Percentile 25% (Q1)	13.1
Maximum	18.0	Percentile 75% (Q2)	14.7

Table 5.3: Summary of B2B Carbon Footprint Results

delivered to the customer. This B2B carbon footprint value includes all of the activities shown in Figure 5-6, except the activities of the retailer, consisting of the Customer DC, Transport to Store, and Store stages. Though the average B2B carbon footprint is 14 kg CO_2e, the actual value when accounting for the variability in retail customer location ranges from 11 to 18 kg of CO_2e based on the actual path required to reach a specific retail customer location. When the 3 kg CO_2e contributed by the retailer's operations is added to the B2B carbon footprint this produces a range of 14 to 18 kg CO_2e per box for the full supply chain carbon footprint. This includes variation due to the efficiencies of each ocean shipping service, transportation distances from ports to DCs and DCs to customers, and relative efficiencies of the different ports and DCs. A summary of the results is shown in Table 5.3 and a histogram showing the distribution of B2B carbon footprints is shown in Figure 5-7.

A visual representation of the B2B carbon footprint serves to highlight the role of location and distance in the calculation. Figure 5-8 shows the B2B carbon footprint as calculated for any point in the country. The results were generated by first calculating the cradle-to-gate carbon footprint for a box of bananas at each DC. The final B2B carbon footprint for any location was then calculated by first finding the distance from the specific location to the closest DC. The emissions generated by ground transportation for that distance were calculated and added to the cradle-to-gate carbon footprint at the DC. The B2B carbon footprint was calculated in this manner for a grid of destination points throughout the United States and imported to ESRI's arcGIS software. Interpolation was then used to estimate the B2B carbon footprint for all points throughout the country and display the results.

The map clearly shows the effects of differences in trucking distance and the efficiencies of the various ocean services. The port of Gulfport, Mississippi requires the lowest emissions to

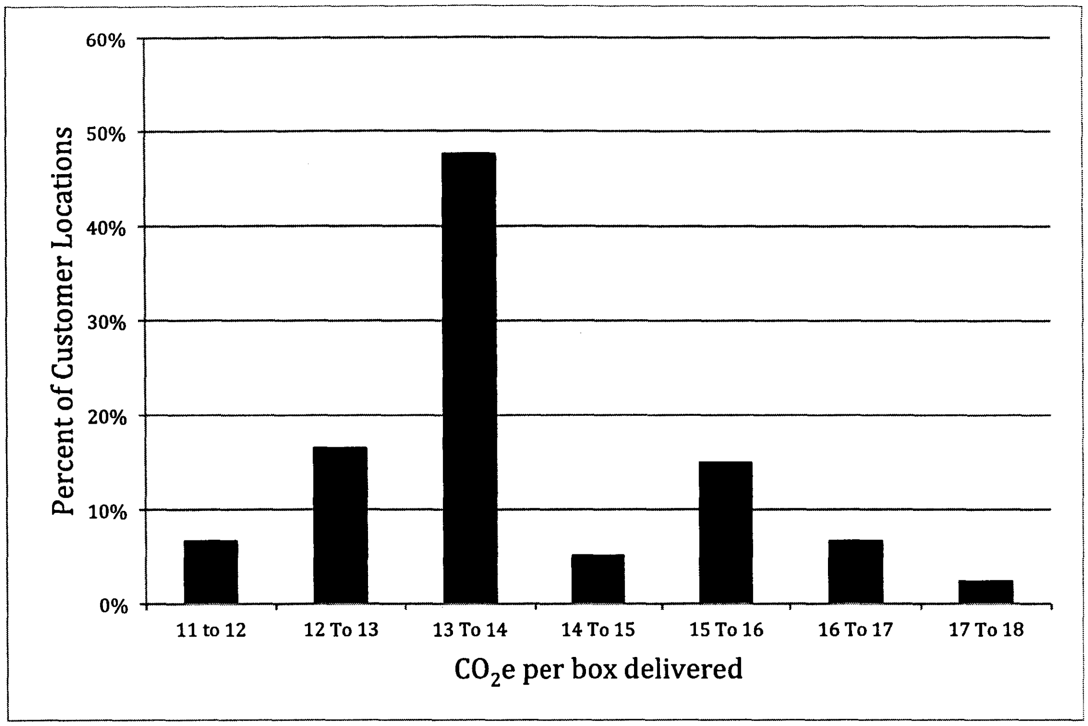


Figure 5-7: Distribution of B2B Carbon Footprint

be reached from the tropics, and combined with the proximity of a DC in New Orleans results in the lowest carbon footprint for products sold in the Southeast. In contrast, the lower efficiency of the West Coast ocean service and the significant trucking distance required to reach the Pacific Northwest results in the highest carbon footprint for customers in this area. Customers on the East Coast have close access to a number of DCs resulting in relatively low carbon footprints, while customers in the Midwest often have significant distance to the closest DC, or require a lengthy haul from the port to the DC near Denver. Thus, the B2B carbon footprint for any particular customer is highly dependent on the specific structure of the supply chain.

5.1.3 Discussion

In this section we have analyzed the sources of uncertainty and variability in the carbon footprint of bananas. Sharing information with downstream customers was one proposed method for improving the quality and reliability of the results. The decision to share this

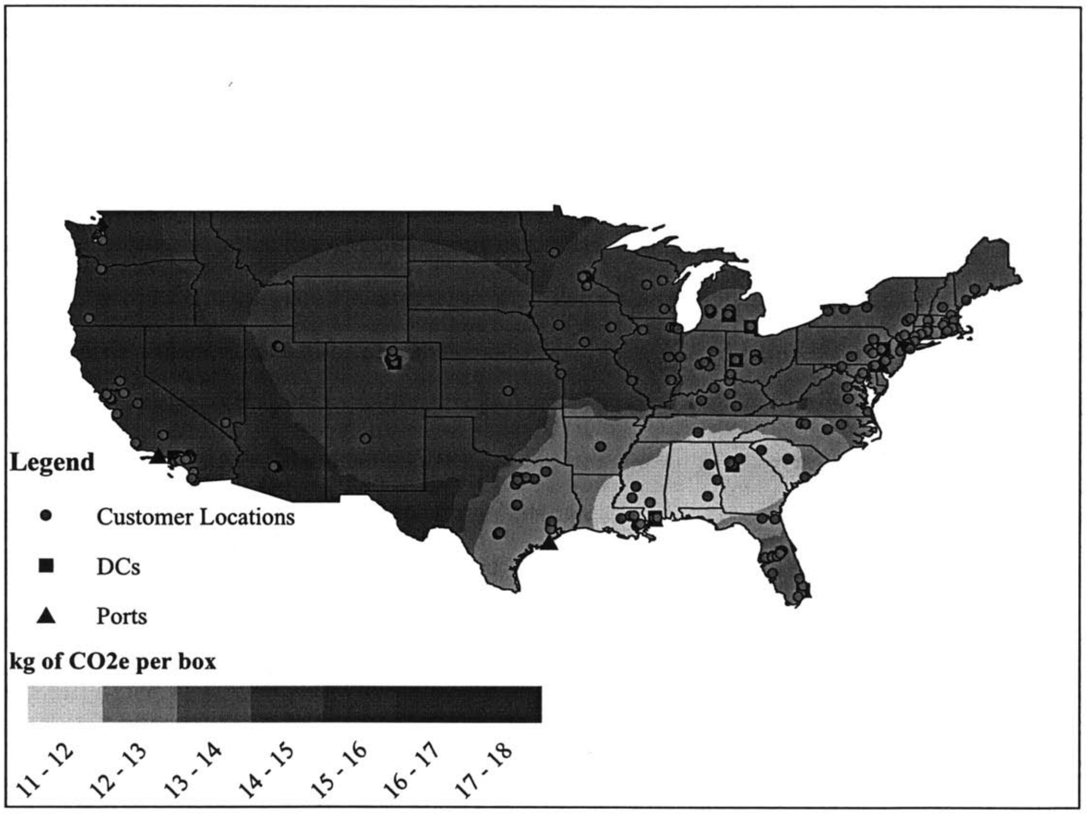


Figure 5-8: B2B Carbon Footprint by Location

information with customers raises questions related to how variability within the supply chain should be handled, as our results show that the carbon footprint of bananas sold to different customer locations can have significant variability. In Section 5.2 we review the literature on information sharing within the supply chain to gain insight on how it works in the context of a supply chain. We identify the characteristics necessary for a good information sharing scheme and relate these characteristics to the prospective sharing of carbon footprint data.

5.2 Information Sharing in the Supply Chain

An important aspect of supply chains is that they consist of multiple firms (Mentzer et al., 2001). Private information held by each of the firms is inherent in the supply chain (Simatupang and Sridharan, 2002). Sharing information between firms is one method of improving coordination (Simatupang, Wright, and Sridharan, 2002), and it has been cited as a fundamental need for supply chains to improve performance (Barratt, 2004).

Several reviews of the literature have classified the work on information sharing based on the information shared and its uses. Huang, Lau, and Mak (2003) provide a review of work related to the impact of sharing production information in the supply chain through a reference framework of seven key elements. Lee and Whang (2000) identify a number of examples of information sharing in supply chains, including inventory levels, sales data, order status, forecasts, production/delivery schedules, capacity, and performance metrics. Sahin and Robinson (2002) divided the literature in to three categories based on the degree of information sharing and flow coordination: no sharing and no coordination, partial or full sharing with no coordination, and full information sharing and coordination.

A number of previous papers have focused on the role of information sharing in solving specific problems. One of the most well known uses for information sharing is in reducing the bullwhip effect. By sharing customer demand data the information distortion normally propagated up the supply chain can be reduced (Lee, Padmanabhan, and Whang, 1997; Chen, Drezner, Ryan, and Simchi-Levi, 2000). Other work has focused primarily on inventory systems. The work is often directed towards finding the best inventory strategy under a number of different information sharing arrangements and quantifying the benefit (Yu, Yan, and Cheng, 2001; Cachon and Fisher, 2000; Lee, So, and Tang, 2000). Additional work has focused on issues such as the role of information technology in enabling information sharing (Rai, Patnayakuni, and Seth, 2006) or empirical studies related to its role and effect within the supply chain (Zhou and Benton Jr, 2007; Spekman, Kamauff Jr, and Myhr, 1998).

Many studies assume that information sharing partnerships will result in a win-win outcome without rigorous analysis (Yu et al., 2001). Cachon and Fisher (2000) noted the wide range of estimates for the value of information sharing, and that the actual benefits may be related to factors other than the additional information. Li (2002) showed that with strategic behavior information sharing does not always result in an overall benefit.

Given the perceived importance of information sharing in the supply chain, the range of possible applications for the information, and the divergent results on the value of the information this raises the question of what makes for an effective use of information sharing. Lee and Whang (1999) propose that there are three criteria for a "good" information sharing scheme in the context of a decentralized inventory management process:

1. Cost Conservation
2. Incentive Compatibility
3. Information Decentralizability

Cost conservation means that all costs must be accounted to individual sites. Incentive compatibility requires that each manager finds it in his or her interest to make the optimal decision for the system as a whole. Information decentralizability means that the scheme can be implemented with only the information available at the site.

A key aspect of supply chain management is the shift in focal point from business units to supply chains (Lee and Whang, 2000). This shift in focus is similar to the change in perspective required when moving from an organizational perspective of carbon accounting to a life cycle approach. With this in mind we consider the application of Lee and Whang's (1999) three criteria to the issue of suppliers sharing the carbon footprint of their products with customers.

In order to meet the criteria for cost conservation it is necessary that the firm fully account for the emissions of its scope 1 and scope 2 activities, as well as all the upstream scope 3 activities of its suppliers. With these emissions accounted for the firm must pass this full accounting of emissions on to its customers to fulfill the cost conservation criteria. This is similar to the approach for product, value chain, and corporate carbon accounting by the GHG Protocol discussed in Chapter 3.

With scope 3 emissions data provided by its suppliers any firm should be able to calculate the carbon footprint simply by accounting for its scope 1 and scope 2 emissions and adding them to the scope 3 emissions supplied by their upstream partners. The 2011 Carbon Disclosure Project (CDP) (CDP, 2011) reported that 306 of the S&P 500 firms responded to their survey by disclosing their GHG emissions. This high rate of GHG disclosure (91% of respondents) indicates that at least large firms should have the information necessary to account for their own scope 1 and scope 2 emissions. When combined with the scope 3 emissions provided by their suppliers the firms should then have the information necessary to fulfill the requirement of information decentralizability.

Where the proposed sharing of carbon footprint information fails is in the context of incentive compatibility. In order for a system to be incentive compatible each manager must find it in his or her best interest to make the optimal decision for the system as a whole, but managers may have incentive to falsely report information on their carbon footprint. Without a method to verify the true level of emissions firms can underreport emissions and be perceived as better performing. The lack of trust represents the biggest obstacle to information sharing in supply chains (Li, 2002). Lee and Whang (2000) caution that firms would be naive to assume information sharing will automatically produce better results, as firms incentives are not always aligned and firms are reluctant to disclose sensitive data. Thus, without verification of carbon footprint information managers may not have incentive to truthfully report emissions, potentially leading to decisions that are not optimal for the supply chain.

This lack of trust has been specifically noted in the literature on environmental monitoring in supply chains. Thomas and Griffin (1996) considered environmentally conscious supply chain management as an emerging research area in supply chain coordination. Vachon and Klassen (2006) identify the use of environmental monitoring as one of two possible approaches to environmental management. Environmental monitoring involves gathering and processing supplier information through public data, company specific questionnaires, or the use of audits (Min and Galle, 2001) The lack of standards and third party verification related to environmental reporting represent a barrier to adoption of CSR practices across the supply chain (Faisal, 2010)(Jenkins and Yakovleva, 2006). In order to remove the barrier to information sharing represented by the lack of trust we propose the use of a carbon label program as a method to increase confidence. In the next section we present a framework for how carbon labels can be used to share data with supply chain partners.

5.3 Carbon Label Framework

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 (1970) examined how this asymmetry can create inefficiencies in the market. 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 reduce the data quality problems currently associated with LCA by providing 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; and testing can provide an objective measure of the claim (Golan, Kuchler, Mitchell, Greene, and Jessup, 2001). The Carbon Trust is an example of a current third party certification program for carbon labels. Companies wishing to obtain the Carbon Trust label may measure their carbon footprint in accordance with the standards set forth by the British Standards Institute PAS 2050 standard. The Carbon Trust then provides auditing and certification services that are required to use their label. 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 et al., 2001). 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 et al., 2001). No single approach to traceability is adequate for every system, and the characteristics of a good traceability system cannot be defined without considering the system's objectives. However, the traceability system itself can be described by three dimensions: 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 et al., 2004). Any carbon label can therefore be characterized in terms of these three dimensions, and the appropriate choice of each is dependent on the goal of the label.

5.3.1 Breadth

The first characteristic of the label is its breadth—what is included in the measurement. At the most basic level this covers which gases should be included in the measurement. Given the confusion sometimes surrounding the term "carbon footprint," the label must specify what emissions are included and what units they will be measured in. Beyond the technical details like which gases 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 firm 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.

These decisions impact the banana carbon footprint in a number of ways. A number of gases besides carbon dioxide are produced during the course of the banana's life cycle. Refrigerants released from refrigeration equipment and nitrous oxide released from soil both represent significant non-CO_2 sources of emissions in the carbon footprint. If only carbon dioxide is included in the breadth of the banana carbon footprint measurement then the total carbon footprint is reduced by nearly 25%.

Clearly, emissions from activities and materials directly involved in the production and distribution of the product should be included, but inclusion of other activities and materials is less clear. Capital goods that are not directly used in the product's supply chain represent one such decision. Though 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 et al., 2007). Capital goods and infrastructure are required to transport, store, and ripen bananas. This includes trucks, ocean vessels, ports, roads, buildings, refrigerated containers, pallets, forklifts, and a number of other items used throughout the supply chain. Recalculating the carbon footprint with impacts from infrastructure in the Ecoinvent database included raises the carbon footprint by 4%.

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 accounting for these emissions. Many emissions produced by a firm will be the result of activities that are common or joint across several different products, and how those emissions should be allocated to the different products must be determined. We consider that question to fall under the dimension of precision. The idea of breadth 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 emissions should be included, but the question of how to allocate emissions from activities that fall within the breadth of multiple products is related to precision. Breadth 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.

5.3.2 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, and Checkel, 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 fuel consumption. This ignores the other steps in the supply chain required to prepare fuel for use, such as extraction, refining, and transportation. LCA normally takes 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, Faaij, and Neelis, 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 consumers can take 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.

These activities may produce significant emissions, as estimates from our sensitivity analysis show that the addition of consumer travel to the store could add 20% to the carbon footprint of purchased bananas. We assumed the consumer transportation consisted of a round trip distance of 6.41 miles, the mean distance of trips reported as shopping/errands by the 2009 National Household Travel Survey (Santos, McGuckin, Nakamoto, Gray, and Liss, 2011). Vehicle operation was modeled in SimaPro using an Ecoinvent process for a gasoline passenger vehicle. This process is based on an assumed fuel consumption of 25.7 miles per gallon. The total trip emissions were allocated to bananas based on data provided by Shaw's that showed bananas represented 6.7% of the average total purchase price for consumer purchases that included bananas. This results in an estimated 0.2 kg of CO_2e per trip allocated to bananas. Assuming a purchase of 1 kg of bananas (the approximate size of one bunch), this represents a significant contribution to the total life cycle emissions, as this would result in a 20% increase in the estimated impact of 1 kg of CO_2e per kg of bananas. The results are obviously sensitive to assumptions regarding the trip distance, the number of other stops made during the trip, average fuel economy, and total purchase size, but demonstrate that even for products with limited use phase emissions consumer behavior can play a significant role in the total life cycle emissions.

Determining how to handle the use phase is a controversial issue, especially between carbon footprints designed for B2B reporting and those designed for reporting to consumers (Finkbeiner, 2009). The GHG Protocol Product Standard and the PAS 2050 specification both allow for the inclusion of the use phase through the creation of specific use profiles that describe the activities that make up the use phase (BSI, 2011; WRI and WBCSD, 2011b). By combining the use profile with specific emissions factors, the use phase can be quantified and reported to provide a full life cycle perspective. The process for developing the use profile calls for development of specific product category rules (PCR) that specify the use profile for a specific products within that category. Where such PCRs are available firms are expected to comply with guidelines. However, when no PCRs or guidelines are available, firms are able to define their own use profiles (BSI, 2011).

Changes in the depth of the standard can have clear effects on the measured carbon footprint, but it also creates challenges in information collection, calculation, and reporting. The depth of a carbon label must specify which stages of the supply chain should be included in the system boundary. For activities that occur in the future, such as use and disposal, the label must provide guidance on how the activities should be quantified and reported.

5.3.3 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, how to separate emissions between products of different supply chains, 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. Our analysis of the banana supply chain calculated the carbon footprint separately for North America and Europe due to the differences in the supply chain for products sold in each market. However, our variability analysis showed that even within a single market the results can vary significantly for different customers. 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.

Precision must also specify how emissions from joint activities are separated between different products. In LCA three primary techniques are used to handle process that produce multiple outputs: subdivision, system expansion, and allocation (Ekvall and Finnveden, 2001). In subdivision a more precise functional unit is defined, or more precise data is gathered, that allows separation of the production of the products. When subdivision is not possible either system expansion or allocation must be used. In system expansion the boundary of the system is expanded to include the full life cycle of all products produced in the multi-product system. The impact of the product of interest would then be calculated by removing the impacts of the other products from the total impact of the multi-product system. This approach requires collection of extra data from the life cycle for the other products, as well as the ability to calculate the impacts of those products through an alternative production process in order to credit the expanded product system with their removal. Finally, allocation involves using a method to partition the impact of the multi-product process between the products produced (Ekvall and Finnveden, 2001).

The precision must also specify the appropriate use of secondary data. 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 of electricity are available through the EPA at the level of specific power plants, averages by energy provider, averages from electricity generated in specific states, averages at the regional grid level, and at the average national level. The choice of factor can produce significantly different results, as the average emissions rate for electricity generated in Vermont was only 6 lbs/MWh compared with 2,386 lbs/MWh for electricity generated in the state of North Dakota (EPA, 2007). The use of more precise emissions factors is not necessarily better, as due to the distributed nature of the electricity grid the use of regional grid factors may be more applicable than state-level factors. 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 and types of chemicals in the growing process. Our sensitivity analysis showed that the amount of chemicals used at the farm is one of the largest sources of uncertainty in the carbon footprint. Even within the same farm different amounts of chemicals may be used during different time periods due to changes in growing conditions. The work required to measure the carbon footprint at a high level of precision may be very difficult given the complexity of supply chains and LCA. 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.

5.4 Conclusion

In this chapter we have reviewed sources of uncertainty and variability in our use of Life Cycle Assessment to measure the carbon footprint of bananas. Much of the uncertainty in the measurement comes from the lack of visibility upstream and downstream in the supply chain. More than 50% of the carbon footprint for bananas occurs as part of the scope 3 emissions for CBI despite their significant control and visibility to the supply chain. Having suppliers share information with their downstream customers regarding the carbon footprint of their products has been proposed as a method for reducing this uncertainty. However, the significant variability that can exist in the supply chain represents a difficult issue for firms in deciding how best to provide information to their customers.

We have reviewed the literature on information sharing in the supply chain, and identified how the three properties of a "good" information sharing scheme proposed by Lee and Whang (1999) apply to sharing of carbon footprint information. While the proposed carbon information sharing scheme appears to be able to meet the cost conservation and information decentralizability properties, it lacks true incentive compatibility. Because the carbon footprint is a credence attribute it can be impossible for customers to verify the results, and thus firms may have incentive to report lower emissions. We have proposed the use of a carbon labeling scheme as a method for resolving this issue.

We developed a framework for measuring the carbon footprint using the idea of a carbon label. A label reduces the information and data issues within LCA by allowing communication of claims about the product's 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 attributes of the measurement needed for a carbon label.

While breadth and depth together define the system boundary for a carbon footprint measurement, the precision determines the usefulness for making specific decisions based on the label. Achieving a high level of precision can be costly, and thus determining the right level of precision is not easy. In the next chapter we explore the necessary level of precision required to make decisions in the supply chain based on the role of carbon in the transportation decision.

Chapter 6

Incorporating Carbon Emissions in the Transportation Decision Process

In the previous chapter we proposed a system where upstream suppliers would share information with their downstream customers through a carbon label. Under such a system with the depth and breadth of the label set, a company would simply need to measure its own emissions. When combined with emissions from purchased goods and services, the total emission for the company and its upstream supply chain would be a fixed quantity. In order to provide information regarding the carbon footprint of its products to its own customers the firm would need to allocate these emissions to its products and customers. In order to support improved performance in the supply chain it is necessary that the level of precision in the measurement be sufficient to support the decision-making process of the customer. In this chapter we review the role of allocation in measuring the carbon footprint of a supply chain, propose the use of an Activity Based Costing (ABC) scheme for allocating emissions to products and customers, and analyze the appropriate precision through an examination of the transportation decision process.

6.1 Allocation

Returning to the case study of the banana supply chain we can see how the allocation process might work. The PAS 2050 (2011) standard specifies that a label is valid for all products sold within a country. With the functional unit set as one box of product sold in the United States, we set the system boundary to include all activities used to produce and deliver bananas to these customers. This process involves a first stage of allocation, as the emissions related to bananas sold in the United States must be separated from those sold in Europe, as well as from other products such as pineapples and plantains that may share some of the supply chain activities with bananas. Once total emissions have been calculated, the emissions are allocated to the final product by dividing the total emissions by the total number of boxes sold in the United States. The result is the average carbon footprint for all boxes sold in the United States, and this value of 17 kg CO_2e is the quantity that would appear on a carbon label.

From the retail customer's perspective the use of the average carbon footprint for CBI may not be sufficient to make reliable decisions. That is, the average value provides a measure that can be used to track the performance of CBI over time—are they improving carbon efficiency on a yearly basis? This reflects one of the primary uses of programs such as the GHG Protocol Product Standard–tracking year-on-year emissions performance. The Carbon Trust Carbon Label requires a pledge to reduce the carbon footprint of the product by a set amount over a two year time period, and failure to do so results in the loss of the right to use the label. This helps create the incentive for firms to reduce their product carbon footprint. However, this does not provide enough precision for a specific retail customer to determine whether CBI has improved the carbon efficiency of the service provided to that customer. CBI's average carbon efficiency could improve on a yearly basis solely through an increase in sales in regions that require less emissions to serve, such as the Gulf Coast region. This provides little help to customers in the Pacific Northwest interested in CBI's performance with respect to the products sold to them.

From a decision-making perspective, however, the use of the average value for the label can result in poor decisions. Given the possible variation in the actual carbon footprint of a product sold to a specific customer any decision based off this value could introduce significant errors. Under a B2B carbon label program, where the total carbon footprint is calculated incrementally at each stage of the supply chain, the error in these average values could compound over time. Our results from Chapter 5 showed that the B2B carbon footprint of bananas sold to specific customers in the U. S. could range from 11 to 18 kg CO_2e, a significant difference. In order to improve the decision making of the supply chain, the label requires a level of precision that reflects the decision being made by the customer. In the rest of this section we review the methods of allocation used in LCA and cost accounting before presenting ABC as a method that can be used to allocate emissions at a level of precision needed to improve decision making in the supply chain.

6.1.1 Allocation in LCA

Ekvall and Finnveden (2001) identify two types of allocation problems in LCA: allocation of the environmental burden in multi-process systems and in open loop recycling scenarios. Within multi-process systems Frischknecht (2000) identifies three distinctive features of processes that may affect the type of allocation used:

- Joint or combined production of goods.
- Simultaneous or successive production of goods.
- One or several decision-maker(s) involved.

Differences in the production process may lead to a number of different allocation procedures, with multiple studies of similar systems taking different approaches (Frischknecht, 2000). The choice of allocation can be an important decision, as in some cases the choice of approach may have more influence on the final results than any other parameter (Kim and Dale, 2002).

The ISO 14044 standards developed for Life Cycle Assessment describe a three step process for allocation (ISO, 2006b):

- Step 1: Wherever possible, allocation should be avoided by
  - dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes, or
  - expanding the product system to include the additional functions related to the co-products, taking into account the requirements of 4.2.3.3.

- Step 2: Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them; i.e., they should reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system.

- Step 3: Where physical relationships alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products.

The subdivision of a process into sub-processes only avoids the allocation problem when the process is composed of single-function sub-processes for which environmental data can be obtained separately (Ekvall and Finnveden, 2001). While a process may be physically separable in to sub-processes it is unlikely that changes in one will not affect the other unless they are economically separate as well. Thus, the sub-division process will be accurate only if the sub-processes are physically and economically separate (Ekvall and Finnveden, 2001). Despite the guidance supplied by the ISO standards and the use of sub-division and system expansion, avoiding allocation in all cases is generally seen as impossible (Weidema, 2000). However, the ISO standards call for sub-division to be used when it can reduce the allocation problem, even if it cannot completely eliminate it (Ekvall and Finnveden, 2001; ISO, 2006b).

The use of allocation despite the guidance to use system expansion may be partially explained by differences in study types, as Tillman (2000) states that the choice of allocation method should depend on the type of study. In attributional studies an allocation procedure is appropriate, while for consequential studies a system expansion method is appropriate. For attributional studies system expansion is often not possible because they describe the status quo and no change in production volume occurs (Weidema, 2000). System expansion is appropriate for use when comparing alternative scenarios for the same product, though some studies have used it to compare different products (Ekvall and Finnveden, 2001). Even attributional studies can use system expansion by employing market data to describe what could have happened under hypothetical system expansion (Weidema, 2000).

Most approaches to allocation have employed either an allocation based on physical units or economic value (Azapagica and Clift, 1999). The physical causality allocation basis means that burdens should be partitioned between different functions of the system to reflect the underlying physical relationships between them and not in proportion to a simple measure. Physical causality requires some quantitative method that describes the behavior of the production system, usually a mathematical model (Azapagica and Clift, 1999). Allocation in joint processes is often carried out for competitive reasons rather than discovery of an absolute truth, and thus should be performed by the party responsible for the process (Frischknecht, 2000). A basic principle of the ISO standards is that the sum of the allocated burdens should equal the total of the unallocated burden (ISO, 2006a).

6.1.2 Cost Accounting

The internal accounting function of a company fulfills two purposes: decision-making and control. The control purpose is served by including accounting information as part of performance measurement, while the decision-making purpose is designed to provide the knowledge necessary for informed decisions (Zimmerman, 2006).

A cost object is a product, department, program, or process for which we wish to determine the cost for. The cost for a cost object is the sum of its direct costs and allocated share of indirect costs. Direct costs are those that can easily be traced directly to a product. Indirect costs, also called common costs or overhead costs, arise from a resource that is shared by several products. Allocation is the process of dividing the common costs between the cost objects. The process of allocation is comprised of three steps:

1. Defining the cost objects

2. Accumulating the costs to be assigned to the cost objects

3. Choosing a method for allocating the costs to the cost objects

In order to perform step three an allocation base must be chosen. This is the measure of activity associated with the common cost that can be used to distribute the common costs to the cost objects (Zimmerman, 2006).

In traditional cost accounting, allocation using a base that does not reflect the actual cost drivers, along with the classification of many discretionary costs as fixed, can lead to distorted ideas of product cost (Cooper and Kaplan, 1988a). Traditional cost accounting was mainly concerned with providing information for external reporting (Bakke and Hellberg, 1991). The focus on external reporting and the distorted idea of product cost has led to the creation of new management accounting approaches, such as Activity Based Costing.

Unlike traditional cost accounting, ABC is more concerned with identifying the actual costs of products and activities to improve management decisions (Bakke and Hellberg, 1991). In an Activity Based Costing system costs are first traced to specific activities, and then from activities to specific customers. In this manner it provides more accurate information to managers that can be used to help make decisions (Cooper and Kaplan, 1988b). Traditional cost systems tend to view an organization as a series of functional blocks, while activity based systems view it as a series of linked activities that deliver value to the customer. The focus in activity-based management is on understanding the activities, costs, and how they link together in the value chain (Morrow and Ashworth, 1994). This focus is key when taking a supply chain view, as activity-based information can provide relevant information about activities across the entire chain in order to improve competitive advantage (Berry et al., 1997). ABC is seen as well suited for the measuring performance and costs of logistics systems (Pohlen and La Londe, 1994), and a number of sources have proposed forms of ABC as appropriate for supply chain management (Pirttilä and Hautaniemi, 1995; Liberatore and Miller, 1998; van Damme and van der Zon, 1999; Dekker and Van Goor, 2000; Goldsby and Closs, 2000; Manunen, 2000; Stapleton, Pati, Beach, and Julmanichoti, 2004).

6.1.3 Applying ABC to the Carbon Footprint of a Supply Chain

There are several similarities between the discussion of allocation in LCA and the application of management accounting to supply chains. In theory every decision should be based on opportunity costs, however, this requires a special study for every decision. In practice, this can be a difficult and time-consuming practice, for which accounting costs are often used as a shortcut (Zimmerman, 2006). This is true in LCA as well, where it is still common to see attributional studies applied for consequential purposes (Weidema, 2000). LaLonde and Pohlen (1996) propose a system called supply chain costing that employs the techniques of ABC, but applies them across organization boundaries. However, this process involves gathering activity data for all firms in the supply chain, many of which may not be willing or capable of providing this data. Similar issues of data access occur in LCA, and can be exacerbated by the use of system expansion, which can expand the system boundary to include the life cycle of additional products (Kim and Dale, 2002). The need to collect data from additional product systems is justified only if the information results in significant value for a decision based on the results. This generally requires that the indirect effects of the change are significant and the uncertainties are not large (Ekvall and Finnveden, 2001).

We contend that in the typical management activities of a supply chain, the use of accounting data for most decisions would indicate that the effort required to collect additional information on the system is not justified, otherwise most decisions would involve a full analysis of the opportunity costs. It may be that decisions made at the strategic level or by customers that have the ability to significantly change a supplier's operations are worthy of this level of analysis. For these decisions the indirect effects are large and the importance of the decision justifies the extra cost of collecting marginal data and analyzing opportunity costs. In such cases it may be more appropriate to make use of a consequential approach to LCA and employ system expansion to consider the indirect effects of the action. For tactical or operational level decisions where the decision is unlikely to cause significant indirect impacts this effort is unlikely to be feasible, and an attributional LCA using an allocation approach should be sufficient for most applications involving carbon footprint data. The carbon footprint data provided by suppliers can thus serve as a shortcut to performing full consequential LCAs in the same way that accounting costs are used in place of opportunity costs.

The use of accounting principles has previously been applied to environmental issues in two ways. Ratnatunga and Balachandran (2009), for example, identified management accounting as a useful tool in the new-carbon economy, where costs associated with carbon emissions over the whole life of a product must be considered. In this case it is the financial costs of the carbon emissions, such as through carbon taxes or regulatory compliance, that must be allocated to products. Mamouni-Limnios, Ghadouani, Schilizzi, and Mazzarol (2009) employ a different approach, using ABC to calculate the ecological footprint of products. Our method is similar to the latter approach, as we propose using ABC to allocate the actual environmental impacts to the products and customers and not simply the costs associated with them.

We propose this because ABC is not just well suited to use in the supply chain, but also specifically to our approach to measuring the carbon footprint of the supply chain. Morrow and Ashworth (1994) describe ABC as a tool for calculating how the input costs from suppliers and the production processes of the firm relate to its outputs. This echoes our approach to calculating the carbon footprint where firms take information regarding the carbon footprint of their inputs from suppliers and add the carbon emitted from their own processes to calculate the carbon footprint of their outputs. Further, the process of performing Activity Based Costing closely resembles the allocation process defined for LCA.

Consider the seven step method used by Lin, Collins, and Su (2001) for implementing ABC for supply chain management:

1. Selecting the team.
2. Analyzing the supply chain functions.
3. Breaking process down into activities.
4. Identifying the resources consumed in performing the activities.
5. Determining the costs of the activities.
6. Tracing the costs to the cost objects.
7. Analyzing the final cost information from a total cost perspective.

We propose that this same seven step process could be performed for calculating the total carbon footprint instead of the total cost. Steps three to five closely resemble the first step of the process proposed by the ISO standards. Step three is similar to the idea of subdivision, as the process is broken down into individual activities. In steps four and five the resources consumed and costs of those activities are determined, similar to the collection of input and output data of the individual sub-processes. In step five, rather than identify the financial cost of activities, we instead propose to determine their carbon footprint. Thus, instead of using financial information to calculate the cost of activities, we instead use LCA information to calculate the total carbon footprint of each activity and trace the carbon emissions to specific cost objects. Finally, in step six the costs (or carbon footprint) are traced to cost objects based on their use of various activities. Thus, the allocation is based on a method that reflects the relationship between the activities and the emissions generated, consistent with the principles outlined in step two of the ISO process. This process solves the issue identified by Schmidt (2009), where allocating emissions by value or production volume no longer reflects the technical-causal or ecological conditions in the production process.

6.1.4 Discussion

In this section we identified the role of allocation in the process of sharing carbon footprint information with customers. We have proposed an Activity Based Costing approach to allocation as being appropriate for use by firms due to the similarity to the process of allocation within LCA and its relationship to supply chain management. The ABC approach is useful for both the measurement of performance as well as supporting improved decision making internally or with key external interfaces.

In the remainder of this chapter we illustrate this concept through an analysis of a transportation decision. Though a number of current carbon measurement programs and standards exist, we show that current programs are analogous to traditional cost accounting approaches, relying on allocation by total volume rather than identifying the activities that drive emissions. We propose new approaches for the mode and carrier selection process that separates transportation to its component activities and allocates the emissions to customers based on how these activities are used. In the first example we employ subdivision to separate intermodal movements to the component processes of drayage and rail haul. In the second example we separate truckload movements into direct costs, represented by the direct emissions produced in moving from the origin to the destination, and the joint costs of vehicle repositioning.

6.2 Transportation Decision Framework

The transportation sector is a significant contributor to global greenhouse gas emissions and energy usage. Transportation as a whole accounts for 19% of global energy use (IEA, 2009). In the U.S., with the largest transportation footprint, the sector represents 28% of total greenhouse gas emissions. The International Energy Agency (IEA) predicts emissions from transportation to grow by 50% by 2030 and by 100% by 2050 from 2007 levels (IEA, 2009). The Energy Information Administration (EIA) predicts similar high growth in energy consumption, rising by 39% by 2030 and 92% by 2050 from 2006 levels (EIA, 2011).

Within the transportation sector, freight is expected to experience the fastest growth. Freight accounted for 27% of transportation energy use globally in 2006 (IEA, 2009). In the United States it represented 28% of transportation energy use, or 8% of overall energy use. Freight is expected to grow by 30% by 2050, compared with 20% for the sector as a whole. This growth is not a new development, as emissions from transportation have been increasing for the past 30 years. From 1973 to 1992 emissions and energy use from freight transport grew faster than any other sector in an analysis of 10 industrialized countries (Schipper, Scholl, and Price, 1997). This growth has continued despite pledges by many nations to reduce emissions under the Kyoto Protocol. Canada committed to a 6% reduction of emissions below 1990 levels by 2012, but total emissions rose by 17% by 2009. This includes a 35% increase in the transportation sector, and a 91% increase in emissions from Heavy Duty Diesel road vehicles (Environment Canada, 2011) The struggle to meet this target led Canada to announce it's withdrawal from Kyoto, citing an estimated $14 billion in penalty costs (Austen, 2011). Emissions from transportation have risen even for countries on track to meet their Kyoto targets. Sweden committed to a reduction of emissions to 8% below 1990 levels, and planned to stabilize transportation emissions at the 1990 level by 2010 (Floden, 2007). Despite achieving an 11% reduction in total emissions from 1990 levels, Sweden did not meet the transportation goal, as emissions rose by 9% from 1990 levels by 2010 (EEA, 2011).

In addition to the high emissions associated with freight transportation it represents a key role within the supply chain. Stank and Goldsby (2000) present a framework for

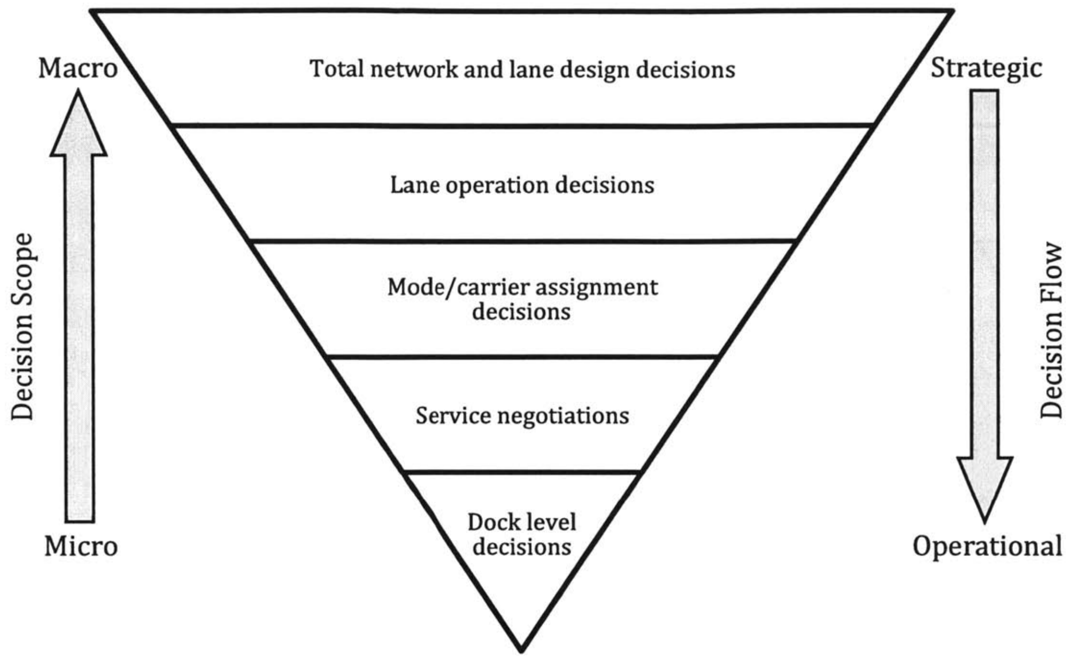


Figure 6-1: Transportation Making in an Integrated Supply Chain (Stank and Goldsby, 2000)

transportation decision making in an integrated supply chain where transportation serves as the connection to suppliers and customers, and successful performance is necessary for the success of the supply chain as a whole. In their framework, shown in Figure 6-1, the types of transportation decisions are characterized by the decision flow, from Strategic to Operational, and the scope of the decision, from Micro to Macro (Stank and Goldsby, 2000).

Using this framework we propose that the information needed by managers to make decisions at each level of this framework differ in their precision, and current carbon measurement programs do not support this integrated framework. In order to demonstrate this we focus on the level of mode/carrier assignment and present analysis that compares current programs available at both the mode and carrier selection level with more precise metrics suitable for use in an integrated supply chain. Specifically, we show that current programs operate at a level of precision suitable for the traditional method of mode/carrier selection defined by Stank and Goldsby (2000) shown in Figure 6-2.

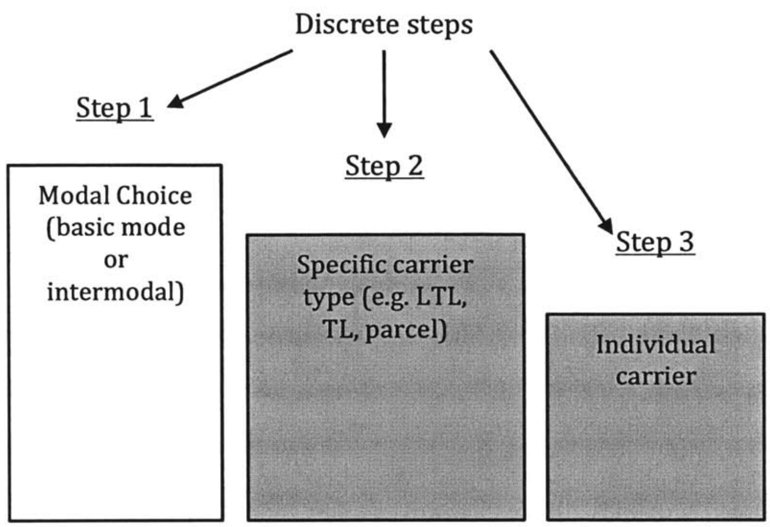
In the traditional mode selection the transportation manager selects a carrier by making three separate distinct steps. First, the basic mode is chosen, such as road, rail, ocean, air, or intermodal. Second, the specific type of carrier within that mode is chosen, distinguishing between different types of transportation that fall within the same mode, such as LTL, truckload, or parcel service for road transport. Finally, the transportation manager selects between the available carriers of the appropriate type (Stank and Goldsby, 2000).

In our analysis we focus on steps one and three of this process. In Section 6.3 we examine the choice of mode in the context of a road-rail intermodal shipment. We review the key concepts from the mode selection literature, identify the role of current carbon measurement programs in making mode selection decisions, and compare those programs with the results of an analysis of the carbon performance of an intermodal operator.

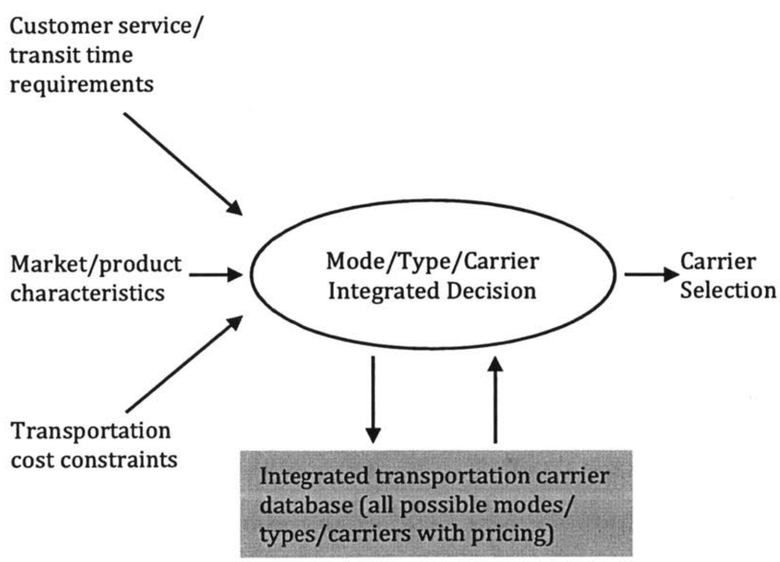
In Section 6.4 we consider the choice of individual carrier selection in the context of truckload carriers. We discuss the carrier selection process with a focus on the use of combinatorial auctions for truckload transportation procurement. We compare the EPA's SmartWay program for measuring carrier carbon performance and show its limitations for use in a combinatorial auction. Finally, using an analysis of the operations of a large truckload carrier, we propose a method for developing lane level metrics suitable for use in a procurement auction.

6.3 Mode Selection

The high rate of growth in freight transport emissions is caused primarily by road transport. Truck transportation is responsible for 90% of freight transportation energy use globally (IEA, 2009). It accounts for more than 60% of the total freight transportation emissions in the United States, moving 40% of all goods by weight and more than 80% by value (Greene and Plotkin, 2011). Since 1991 road transportation has grown at an annual rate of 3.3% in the EU-15, outpacing all other modes of transport (Blauwens, Vandaele, Van de Voorde, Vernimmen, and Witlox, 2006). As countries grow and become more industrialized the increasing shipment of intermediate and final goods results in more use of trucks due to



(a) Traditional Selection



(b) Integrated Selection

Figure 6-2: Mode/Carrier/Class Selection (Stank and Goldsby, 2000) the increased flexibility they offer (Schipper et al., 1997). The growth of freight and share of trucking are coupled with GDP growth, driven by growth in international trade, "just in time" business practices, e-commerce, and handling of intermediate goods (Kamakate and Schipper, 2009). This coupling of economic growth with increased road transportation has significant implications for emissions growth in developing markets, with the vast majority of emissions increases by 2050 coming from non-OECD countries (IEA, 2009).

Given the projected growth in demand for freight transportation, a number of strategies for reducing emissions must be considered. Possible approaches can be grouped into three categories: improved technological efficiency, improved operational efficiency, and shifting to more efficient modes (Vanek and Morlok, 2000). Much of the work in the technological and operational efficiency has been devoted to the trucking industry, as trucking represents the largest share of emissions as well as having a relatively high intensity of emissions per ton-mile (Vanek and Morlok, 2000). However, the increase in demand for trucking has overshadowed any improvements in transport intensity. Over a 20 year period from 1973-1992 road transport energy intensity remained relatively level, increasing by only 2% in the U.S. and EU-8, while the intensity of rail declined by 41% in the U.S. and 23% in the EU-8 during that timespan (Schipper et al., 1997). Given the high levels of emissions associated with trucking even small improvements in efficiency are likely to have a significant impact compared with modal shift due to the difficulty in shifting significant amounts of freight from road to rail (McKinnon, 1999). Other projections are more optimistic regarding the role of modal shift in emissions reductions. The Pew Center on Global Climate Change identified modal shift as having the greatest potential for reducing emissions in the United States, with 5% of the possible 7-10% reduction in emissions achievable by 2030 being the result of improved logistics. This is in comparison to a reduction of only 2% possible through improvements in vehicle technology (Greene and Plotkin, 2011). The IEA's BLUE scenario, designed to achieve the maximum CO_2 reduction in transport by 2050 using measures that cost up to $200 per tonne, projects a 15% reduction in GHG emissions from the baseline scenario due to modal shift from road to rail. When combined with improvements in efficiency (25% reduction) and the use of advanced fuels (15% reduction) this achieves a 50% reduction in emissions from the baseline scenario by 2050 (IEA, 2009).

Reducing emissions through modal shift is achieved mainly through the shift from road transportation to rail. The relative energy efficiency of rail is estimated at two to five times that of trucking, with even the largest trucks being only half as efficient as rail (Schipper et al., 1997). GHG emissions intensities have a similar relationship with trucking, producing twice the amount of emissions that rail does over the full life cycle (Horvath, 2006). Despite the efficiency benefits of rail, a number of factors prevent a significant shift from road to rail, including the high level of service required by modern supply chain practices (Kamakate and Schipper, 2009), access to rail terminals (McKinnon, 1999), and capacity constraints on the railroads (Vanek and Morlok, 2000).

Road-rail intermodal is one popular method for shifting transportation from road to rail, offering shippers the convenience of point-to-point service like trucking combined with the efficiency gains from rail. Despite worries about capacity constraints, intermodal rail units increased by 63% between 1993 and 2005 (Association of American Railroads, 2006). Bitzan and Keeler (2011) estimate that a shift of only 1% of current intercity truck freight to intermodal could generate savings of .92-2.18 Tg of CO_2 per year, an amount equal to 24-56% of the total possible savings available by urban public transit. Thus, while a modal shift to intermodal freight may replace only a small amount of current truckload freight traffic, it is increasingly popular with shippers and can provide benefits on par with other popular policy measures.

Despite the popularity of intermodal as an alternative to trucking, there is relatively little information regarding the actual efficiency of intermodal in comparison to other modes (Bitzan and Keeler, 2011). In this section we attempt to fill this gap in the literature with an analysis of a large data set of intermodal shipments in North America. We compare the results of this analysis with estimates obtained using a publicly available carbon calculator targeted towards shippers and assess the relative efficiency of intermodal in comparison to truckload. In the second part of this section we apply the market area concept to the carbon efficiency of intermodal shipping to explain the difficulty in assessing an overall efficiency for it as a mode. From these results we identify opportunities for intermodal operators to work with shippers to reduce emissions.

6.3.1 Literature Review

In addition to increased popularity with shippers, intermodal transportation has increased as a topic of research (Bontekoning, Macharis, and Trip, 2004). In a review of the literature on intermodal research, Bontekoning et al. (2004) identified eight areas of research. Five of the eight categories focus on issues related to the characteristics of an intermodal shipment, including work on drayage, rail hauls, transshipment, standardization, and multi-actor chain and control. Two other areas of research, mode choice and pricing strategies and intermodal transportation planning and policy, have generated interest in the role of intermodal transportation in reducing greenhouse gas emissions.

At the policy level much of the analysis for the potential of modal shift has been focused on a macro approach suitable for estimating the potential in a given region, but not at a specific company level (Tsamboulas, Vrenken, and Lekka, 2007). In order to provide useful information for shippers and operators at the micro level it would be useful if more relevant data were provided by the actors involved (Bergqvist, 2008). Bitzan and Keeler (2011) noted this lack of available information on the overall efficiency of intermodal when attempting to estimate the potential for a modal shift in US. When attempts have been made to model emissions from intermodal transportation they have generally considered the rail and road segments separately, rather than as a single intermodal movement. Bauer, Bektas, and Crainic (2009) formulate a service network design problem with a goal of minimizing total greenhouse gas emissions and allowing the use of truck or rail in the network. Janic (2007) considers a simplified intermodal network in comparison to a road network in a model that includes both internal costs and external costs related to air pollution, noise, congestion, and traffic accidents. Patterson, Ewing, and Haider (2008) estimated emissions savings from premium intermodal service in the Quebec City-Windsor corridor by calculating truck and rail distances using geocoded locations and then applying emissions factors specific to each mode to estimate emissions. Winebrake et al. (2008) use a Geographic Information System (GIS) approach to model a network using road, rail and water based on geographic data. Their model introduces "artificial" intermodal nodes that connect different network segments, with each network segment having attributes for time, distance, cost, energy, and emissions.

Kim, Janic, and Van Wee (2009) use a multi-modal hub and spoke network that incorporates CO_2 emissions for different modes and at transshipment points. They solve a multi-objective optimization under different constraints on CO_2 emissions to find the pareto optimal solution to the tradeoff between cost and CO_2 under a variety of scenarios in a simplified network.

In each of these cases the emissions from the intermodal shipment were calculated by breaking the shipment into its individual road and rail components. This approach is in contrast to the general perception reported by shippers in surveys that intermodal is its own distinct mode, providing better service than rail, but worse than truckload (Bontekoning et al., 2004). Considering the road and rail segments of intermodal separately has the advantage of more accurately accounting for the rail network during evaluation, but comes at an increased level of complexity required to account for all the possible nodes and links in the network (Macharis, Caris, Jourquin, and Pekin, 2011). In some cases the two approaches may be combined, by first using a detailed network representation to create a set of virtual links that connect the origin and destination, each by a different combination of modes, routes, and equipment (Beuthe, Jourquin, Geerts, and Koul a Ndjang'Ha, 2001). Such a network could have direct links between origin and destination nodes that represent an intermodal shipment (Macharis et al., 2011). Blauwens et al. (2006) use a total logistics cost model that includes transportation costs and inventory costs to explore potential shifts between modes under different policy options. They compare road transport with rail/road and barge/road intermodal. Each option is considered a distinct mode with an associated cost and lead time. While this approach may more closely resemble the decision made by the shipper, it first required a case study to determine the cost and lead times of the different modes. Given the lack of publicly available information regarding the carbon efficiency of intermodal as a distinct mode, such approaches may be difficult to implement.

6.3.1.1 Carbon Measurement Programs

A number of programs exist that provide standards for estimating the greenhouse gas emission from freight transportation (Hoen, Tan, Fransoo, and van Houtum, 2010). Two of the most popular are the GHG Protocol corporate accounting standard and the Network for Transport and Environment (NTM) calculator. NTM is a non-profit organization located in

Sweden with a goal of establishing a base of values for calculating the environmental performance of transportation, and offers a calculation method among its services (NTM, 2012). These programs generally provide emissions factors for freight transportation that account for the fuel consumption of different vehicle types as well as their load size and utilization. This allows for calculation of the carbon footprint of a shipment based on the weight and distance of the shipment using the appropriate emissions factor.

The GHG Protocol (WRI, 2011) provides two sources for the emissions factors, one from Defra for the U.K. and one from the EPA for use in the United States. The EPA factors were created for the EPA's ClimateLeaders program, and employ a top down methodology to calculate emissions factors by mode (EPA, 2008b). Total emissions by mode are estimated from data provided by the EPA's national greenhouse gas inventory (EPA, 2007). The total emissions are then divided by the estimated ton-miles carried by the mode using data from the Federal Highway Administration statistics that uses a survey approach to estimate distances and load factors by mode type (FHWA, 2005). This produces an emissions factor in terms of kg of CO_2 per ton-mile for each of the major freight modes: road, rail, water, and air.

The emissions factors provided by Defra (2010) are similar, but more comprehensive than those supplied by the EPA. Emissions factors for road are supplied for a number of different equipment types within the mode. The methodology makes use of survey data to estimate fuel efficiency and average loading factors by equipment type. These two pieces of data are then combined to calculate an emissions factor in kg of CO_2 per tonne-km for each equipment type. For rail service Defra relies on statistics collected by the Office of Rail Regulation on total consumption of diesel and electricity by freight trains and the total freight moved for trains operating in the UK. The total CO_2 is calculated from the diesel and electricity consumption, and this is divided by the total tonne-km of freight to produce the final emissions factor.

The NTM methodology takes a different approach than those used by the EPA and Defra, relying instead on a bottom up simulation approach. For road NTM makes use of the ARTEMIS emissions modeling software to estimate the fuel consumption of a variety of vehicle types under different load factors and scenarios (NTM, 2010). For rail transport NTM

Mode	GHG Protocol (Defra)	GHG Protocol (EPA)	NTM
Road (light truck)	863	269	368
Road (medium truck)	490	269	258
Road (tractor + trailer)	126	269	92
Rail	31	23	29

Table 6.1: Carbon Intensity by Mode (g CO_2/ton-mile)

uses data based off the EcoTransit model that estimates electricity and fuel consumption for trains under different weight and terrain types (NTM, 2008). The model accounts for transmission and conversion losses in electricity, generation technology mix, and the environmental performance of the different generation technologies. By combining the energy consumption model with assumptions regarding terrain, environmental performance, overall train weight, and the percentage of cargo weight, the model produces an estimated emissions factor, again in kg CO_2 per tonne-km. A free calculator is available for use at the NTM website http://www.ntmcalc.org.

Despite the difference in methodology the end result available for use in calculating emissions is similar across all methods. Users may enter the weight and distance of shipments, and a standard emissions factor per ton-mile is used to estimate total emissions. Some of the relevant emissions factors from the different methodologies are shown in Table 6.1. While each of the methods provides emissions factors for use with either road or rail transport none of the programs provide factors for intermodal. The distance methods available in both the GHG Protocol and NTM require knowledge of the specific routing of the shipment that the shipper may not possess, as the carbon from the road and rail segments must be calculated separately.

The lack of methods available for calculating emissions from intermodal transportation represents a challenge to shippers when deciding whether to shift from truckload to intermodal. The standard multi-modal models used for most mode choice problems require knowledge of the routing, cost, and emissions within the intermodal network. In their survey, Harper and Evers (1993) reported that a high percentage of intermodal shipments were arranged through a third party, and so shippers may have limited information about how exactly the intermodal shipment was transported.

Macharis and Bontekoning (2004) identify four types of operators that may be involved in an intermodal shipment: drayage, terminal, network, and intermodal. Bontekoning et al. (2004) noted that the majority of mode choice models used in intermodal research have been focused at the level of these operators. Even models identified as being targeted towards decision support for shippers, such as those of Barnhart and Ratliff (1993), Bookbinder and Fox (1998), and Min (1991), make use of models based on single mode routing along a multi-modal network.

The intermodal operator is responsible for buying services from the drayage, terminal, and rail network operators (Macharis and Bontekoning, 2004). They coordinate the shipment and have visibility to each leg of the journey. Thus, current carbon calculation methods are sufficient for intermodal operators to include emissions in the mode choice decision. This is not the case for the shipper, where intermodal offers a distinct mode of shipment, different from either road or rail. The details and routing of the shipment are often handled by a third party, and the shipper has only limited information regarding the actual routing. To include greenhouse gas emissions in their mode choice decision, shippers require the ability to calculate the emissions from intermodal with only limited information, but relatively little data on the overall efficiency of intermodal as a mode is available. Vanek and Morlok (2000) used a simulation model to calculate the likely energy efficiency of intermodal to be in the range of 1200-2320 BTU/ton-mile. This would correspond to a carbon intensity of approximately 88-170 g CO_2/ton-mile. The International Road Transport Union (IRU) studied nineteen routes in Europe, and calculated the total energy and GHG emissions required to service those lanes by intermodal and truckload transportation. Their results estimated the total energy consumption required to service all nineteen routes to be 20-50% less for intermodal than trucking, with emissions savings slightly greater than energy savings (IFEU and SGKV, 2002).

6.3.2 Methodology

A number of different definitions of intermodal transportation have been used in the literature, with no clear consensus having emerged (Bontekoning et al., 2004). Jones, Cassady, and Bowden Jr (2000) identify the use of multiple modes of transportation to provide a

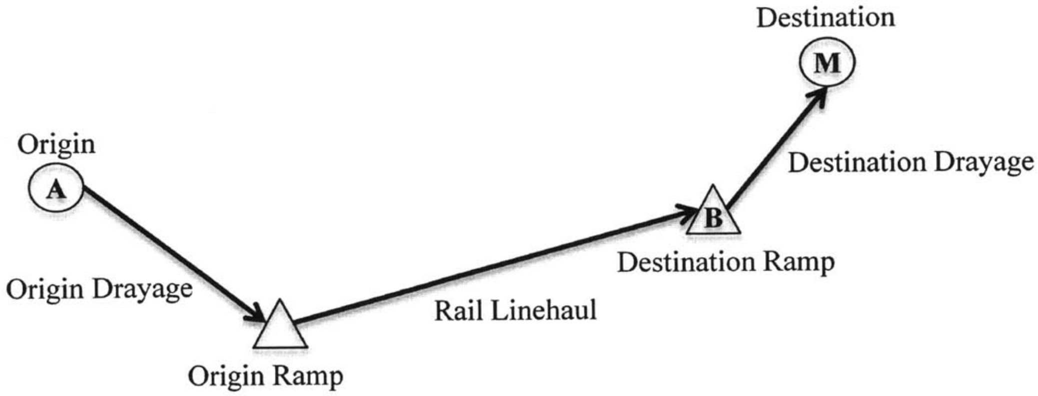


Figure 6-3: Intermodal Movement

single, seamless journey as a primary concept in their definition. These concepts capture the relevant factors for our research. To the shipper, who has the goods requiring movement, an intermodal shipment provides a single movement from origin to destination. The exact modes and intermediate routings are not important, as mode is judged on overall qualities such as speed, service, and cost. In this analysis we limit our focus to the movement of freight through a combination of rail and trucking, which is a common use of the term intermodal (Taylor and Jackson, 2000; Spasovic and Morlok, 1993; Nierat, 1997; Harper and Evers, 1993; Evers, 1994; Nozick and Morlok, 1997).

We define an intermodal shipment to consist of an origin drayage movement performed by truck that takes the shipment from the origin location to the origin ramp. At the ramp the shipment is transferred to rail and a linehaul between the origin and destination ramps occurs. At the destination ramp the shipment is transferred back to a truck and a destination drayage movement delivers the shipment to the consignee at the final destination. This is depicted in Figure 6-3.

We calculate the carbon footprint of an intermodal shipment by disaggregating the shipment in to separate drayage and rail movements using (6.1).

$$C_{IM} = d_{od} \times c_d + d_r \times c_r + d_{dd} \times c_d \tag{6.1}$$

where:

$$d_{od} = \text{distance of origin drayage}$$

$$d_{dd} = \text{distance of destination drayage}$$

$$d_r = \text{distance of rail haul}$$

$$c_d = \text{carbon efficiency of drayage}$$

$$c_r = \text{carbon efficiency of rail}$$

We applied this method to a data set supplied by J.B. Hunt Transportation, the largest intermodal operator in North America. The data consisted of records for more 400,000 individual intermodal shipments covering more than 40,000 origin-destination lanes (grouped by zip code) in North America. Each record contained the zip code locations of the origin, origin ramp, destination ramp, and destination; the length of the origin and destination drayage; and the length of the rail haul. Additionally, the operator supplied a carbon efficiency parameter for drayage based on their own fuel efficiency, empty miles, and out of route miles. The length of the rail haul portion of each movement was provided by the contracted rail companies to the intermodal operator. When this data was not available the rail distance was calculated with the RailMILER commercial software program. The rail carbon efficiency parameter was calculated using efficiency numbers supplied by the rail companies per ton-mile. This value was then multiplied by the average weight of the intermodal shipments, including equipment, to get an efficiency parameter in terms of CO_2 per mile.

The calculation of the carbon footprint of an intermodal shipment in this manner is straightforward, but may be difficult for shippers to calculate in practice. Without knowledge of actual routing the relative distances of the drayage and rail haul movements are unknown. The respective carbon efficiency parameters, expressed in terms of CO_2 per unit of distance, can be estimated from sources such as the GHG Protocol. However, drayage movements tend to be less efficient than standard trucking due to age of equipment (Ang-Olson and Facanha, 2008) and higher empty miles (Spasovic and Morlok, 1993). The use of standard road emissions factors for both trucking and drayage will tend to overestimate the actual efficiency of intermodal shipments compared to trucking. Rail carbon efficiency numbers are generally given in units of CO_2 per ton-mile. These can be converted to distance based factors through a straightforward multiplication of the factor by the shipment weight, but the weight must be adjusted based on the type of equipment used.

These difficulties can be illustrated through a comparison of the calculation of the carbon footprint using actual operator data to a publicly available tool that makes use of limited information. The EPA's SmartWay program provided a method for calculating the carbon footprint of intermodal shipments as part of their original FLEET calculator. The tool is designed to help shippers estimate the potential savings of switching shipments from truck to intermodal. The calculator takes as parameters the distance between the origin and destination and the mix of rail service used (average, mixed freight, double stack, or trailer on flat car). Optionally users can provide specific information on drayage distance, shipment weight, and the percentage of empty drayage miles. The calculator provides an estimate of the carbon footprint of the shipment if moved by intermodal transport, as well as by truckload. This allows the shipper to compare the results and calculate the savings achieved by switching from truckload to intermodal shipments.

The carbon footprint from the calculator was obtained by using the default values for drayage distance, drayage efficiency, and assuming average rail service. Distance was calculated between the origin and destination by first geocoding the zip codes to latitude and longitude values using ESRI's ArcGIS software. Next, the distance between the latitude and longitude points was calculated using the haversine great circle distance formula given by:

$$D = r \times \left\{ 2 \arcsin \left(\sqrt{\sin^2 \left(\frac{\Delta\phi}{2} \right) + \cos\phi_o \cos\phi_d \sin^2 \left(\frac{\Delta\lambda}{2} \right)} \right) \right\} \tag{6.2}$$

where ϕ_o, λ_o, ϕ_d, and λ_d are the latitude and longitude of the origin and destination locations and r is the radius of the Earth. The results from the calculations for both the operator data and the SmartWay calculator are shown in Table 6.2.

From these results we can see that the SmartWay calculator underestimates the total CO_2 by 30% compared to actual data. The large difference in emissions from drayage is mainly due to the SmartWay calculator significantly underestimating the number of drayage miles driven in practice. The SmartWay tool calculates total drayage miles using (6.3) where

	Operator Data	SmartWay Calculator	Difference
Drayage CO_2	173,694	75,041	-57%
Rail CO_2	761,922	582,038	-24%
Total Intermodal CO_2	935,656	657,078	-30%

Table 6.2: Comparison of Intermodal CO_2 Calculations (tonnes CO_2)

D is the distance between the origin and destination locations.

$$drayage = 40 + (\frac{D}{400})^2 \tag{6.3}$$

This produces an average drayage distance of only 57 miles, with a maximum of 86 miles for a shipment with a great circle distance of 2,718 miles. In contrast the operator data shows the average total drayage distance to be 146 miles. The difference in rail CO_2 is driven by a lower estimated rail distance and higher estimated fuel efficiency (15 MPG to 13.8) for the SmartWay calculator.

In order to provide a comparison to other modes of transport, we calculate the carbon intensity of the intermodal shipments by dividing the total CO_2 emissions by the total number of net ton-miles worth of goods moved. Total net ton-miles were calculated by multiplying the shipment weight (excluding equipment) by the great circle distance between the origin and destination for each individual shipment, then summing the total for all shipments. By using the great circle distance between the origin and destination rather than the actual traveled distance we provide a consistent basis for comparing shipments across modes which have different amounts of circuity. Circuity represents the additional distance traveled to reach the destination. For truck shipments this accounts for the need to travel over the road network, which does not run in a straight line between each origin and destination. For intermodal shipments this accounts for the additional road network distance during the drayage movements, the additional rail network distance, and the need to travel to and from the intermodal terminals rather than direct between the origin and destination. Each truck shipment needed to travel an additional 16% farther than the great circle distance, while intermodal shipments traveled 37% farther. Since each mode performs the same work, moving the goods from the origin to the destination, using actual distance traveled rather than great circle distance would fail to account for the increased efficiency of truckload shipping due to the more direct route used.

In addition to the calculated intermodal CO_2 we also include for comparison the estimated CO_2 for serving those same lanes by truckload service. The truckload calculations are again performed using both operator supplied data and the original SmartWay FLEET calculator. Calculations for the operator's truckload emissions are based on data collected from their longhaul trucking business and are calculated using the following equation:

$$CF_{TL} = (d_{otr} + d_{ae}) \times c_{tl} \tag{6.4}$$

where:

d_{otr} =over the road distance

d_{ae} =average empty distance per shipment

c_{tl} =carbon efficiency of truckload transportation

The distance between the origin and destination zip codes is calculated using software that determines the actual over the road travel distance, eliminating the need to adjust the great circle distance using a circuity factor. The average empty miles is a fixed quantity based on dividing the total empty miles traveled by the number of shipments. Finally, the carbon efficiency factor is based on the actual fuel efficiency of the operator's vehicles, an adjustment for out of route mileage variance, and the carbon content of diesel fuel.

The SmartWay calculator uses a slightly different method for estimating truckload emissions, given by:

$$CF_{SWTL} = \left(d_{od} \times d_c \times \left(1 + \frac{d_e}{1 - d_e} \right) \right) \times c_{swtl} \tag{6.5}$$

where:

d_{od} =straight line distance from origin to destination

d_c =circuity factor adjustment

d_e =percentage of empty miles

c_{swtl} =carbon efficiency of truckload transportation

The SmartWay calculator provide default values for the circuity factor of 1.15, the empty

	Operator	SmartWay	Difference
Intermodal CO_2 (tonnes)	935,656	657,078	-30%
Truck CO_2 (tonnes)	1,696,527	1,750,054	3%
Intermodal Intensity (g CO_2/ton-mile)	69	48	-30%
Truckload Intensity (g CO_2/ton-mile)	125	128	3%

Table 6.3: Calculated CO_2 Intensity

miles as 20%, and the carbon efficiency calculated by using a factor of 74.5 g CO_2/ton-mile and an assumed weight of 22 tons. The calculated emissions from intermodal shipping, truckload shipping, and the resulting efficiencies are shown in Table 6.3.

From this we can see that while the SmartWay and operator intermodal calculations lead to significantly different results, the estimates for truckload shipping are fairly consistent. When compared with data for other modes available from sources shown in Table 6.1 we can see that the calculated intensity of intermodal shipping fits in the expected range, with both calculation approaches showing a higher intensity than rail but lower than trucking. The estimated emissions from truckload shipping are consistent with estimates from other sources. Our calculated intensity falls below the range estimated from Vanek and Morlok (2000), but the estimated savings when compared to trucking are consistent with the average range found by the IRU (2002).

Recall that the emissions from intermodal shipping can be broken up into three parts—the origin drayage, the rail linehaul, and the destination drayage movement. The drayage movements are generally considered to be less efficient than truckload shipping, while the rail haul is more efficient. For the overall shipment to be more efficient than truckload the linehaul must be long enough to make up for the lower efficiency of drayage and the increased circuity of the rail network compared to the lower circuity provided by the direct point-to-point truckload shipping. Thus, on a specific shipment the actual efficiency of using intermodal transportation can vary depending on the actual distances involved for each of the three parts.

To show this variation we calculate the intensity of the intermodal movements on a lane-by-lane basis. Each lane is defined as a distinct origin-destination zip code pair, more than 40,000 of which are represented in the data set. For each lane the intensity was calculated

	Operator	SmartWay
Minimum	29	47
Mean	72	49
Maximum	308	67
Std. Dev	15	1.8

Table 6.4: Summary of Calculated Intermodal CO_2 Intensity by Lane

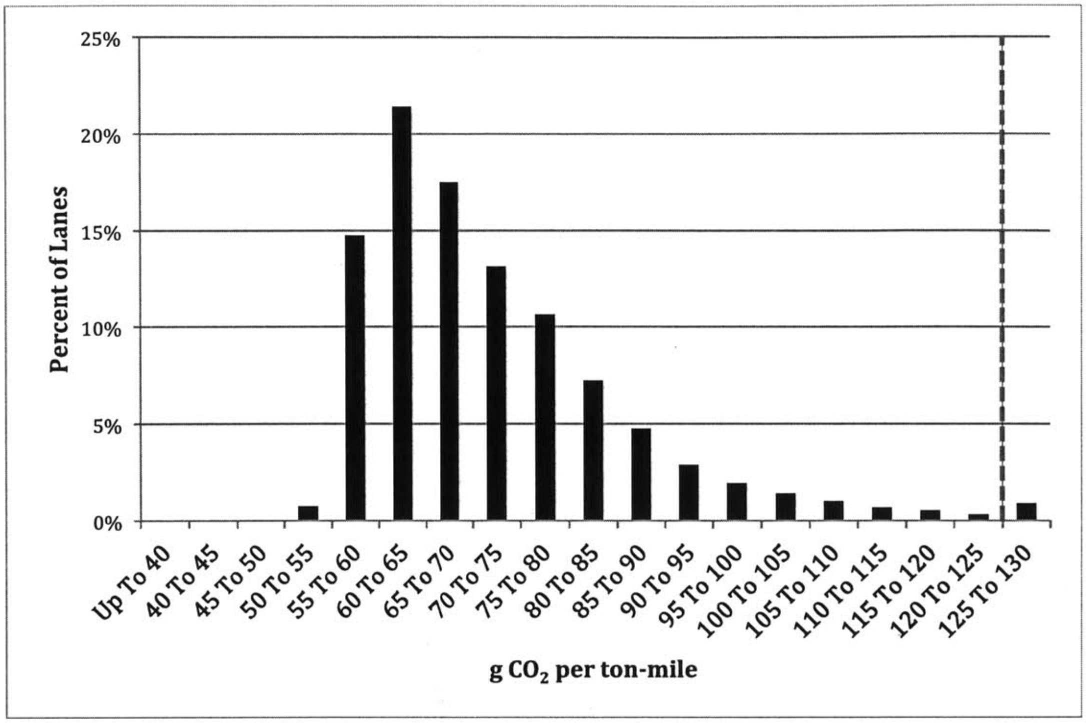


Figure 6-4: Distribution of Intermodal Carbon Intensity by Lane

by dividing the total CO_2 for the lane, as calculated using (6.1), by the total net ton-miles of cargo shipped. As a comparison a similar analysis was done using the SmartWay calculator. A summary of the results from this analysis is shown in Table 6.4. The distribution of the operator's lane-by-lane intensities is shown in Figure 6-4, with a vertical shown representing the 125 g CO_2/ton-mile average intensity of truckload shipping. Due to the assumptions in the SmartWay calculator the calculated intensity shows a limited variation from the average value, with more than 99% of the lanes falling within the range of 45-55 g CO_2/ton-mile.

From the results we can see that the actual intensity for a given lane can vary significantly, and in some cases the carbon intensity may actually higher than if truckload shipping had been used. This is not true for the results from the SmartWay calculator, where no lane shows a greater intensity than if served by truckload and the calculated intensity always falls within a narrow range. This creates difficulty for shippers considering switching from truckload to intermodal, as there is considerable uncertainty about how much carbon savings can be obtained by switching individual lanes. In the next section we further examine the competitiveness of intermodal versus truckload shipping through the concept of the intermodal market area, and show how this concept can be used by intermodal operators to help shippers identify the lanes best suited for intermodal shipping.

6.3.3 Carbon Market Area

The reason for the lane-by-lane variance can be explained through the application of market area theory to intermodal transport. Nierat (1997) describes the market area of intermodal transportation as the region of space around a rail terminal in which intermodal transportation is the most competitive mode. The space is defined around a rail terminal because an intermodal shipment requires a fixed threshold cost to first be moved to the terminal via the origin drayage and rail line haul. The total cost to reach the destination is then this fixed cost plus the cost of the drayage move from the terminal to the final destination. This cost increases as the destination moves away from the terminal due to the longer drayage move at the destination. If the destination is too far from the terminal it may no longer be competitive to use intermodal transportation, instead a direct truckload shipment between origin and destination would be used.

A depiction of the choice faced between intermodal and rail is shown in Figure 6-5. The shipment begins at point A and is destined for point M. If the shipment is sent via intermodal it is first sent to the origin terminal by drayage truck and then to the destination terminal, point B, by rail. This represents the fixed cost portion of the shipment, as regardless of where M is located the shipment must first be taken to point B. From B to M the final movement is again made by drayage truck. If the shipment is instead sent by truck it travels directly from A to M. The intermodal market area for terminal B defines the range of space around B where M can be located and served more competitively by intermodal service than direct truckload shipment given the origin location of A.

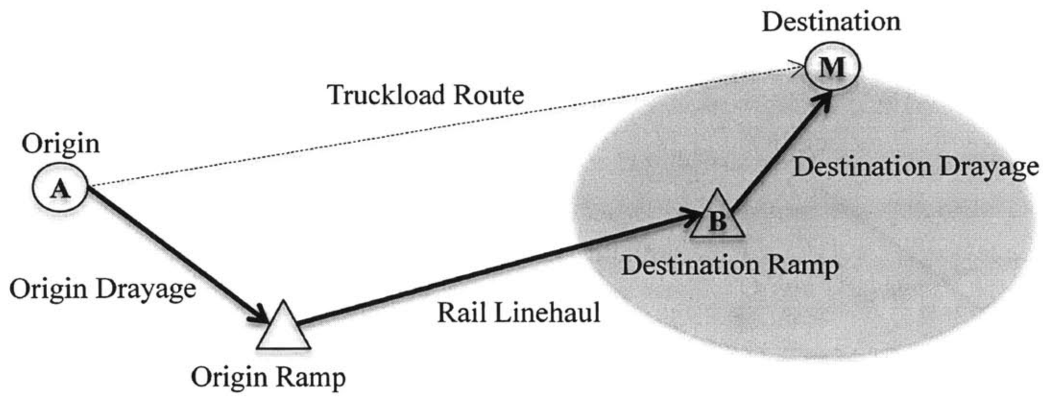


Figure 6-5: Intermodal vs. Road Choice

Formally Nierat (1997) defines this service area by calculating the costs for each shipment in the following manner. The cost to reach point M by road, defined as $C_r(M)$, is a combination of a fixed cost, $C_r(A)$, and a variable cost per unit of distance, ω_r. The intermodal cost, $C_i(M)$, likewise consists of the fixed cost required to reach B, $C_i(B)$, plus a variable cost per unit of distance from B to M, ω_i. The boundary of the market area can be found by setting the two costs equal to one another.

$$C_r(M) = C_i(M) \Leftrightarrow C_r(A) + \omega_r \overline{AM} = C_i(B) + \omega_i \overline{BM} \tag{6.6}$$

Rearranging the terms and substituting $\omega = \frac{\omega_i}{\omega_r}$ and $k = \frac{C_i(B) - C_r(A)}{\omega_r \overline{AB}}$ gives the equation as:

$$\overline{AM} - \omega \overline{BM} = k\overline{AB} \tag{6.7}$$

The parameter ω represents the relative cost of drayage operations to standard road trucking. When $\omega > 1$ the market area will have an oval shape oriented along the direction of travel from A to B. We note the similarity between the method used to calculate the cost of road and intermodal transportation by Nierat (1997) and our previous method for calculating the carbon footprint of shipments sent by those methods. With this in mind we extend this idea by defining the *carbon market area* of an intermodal terminal as the region of space around an intermodal terminal that can be served from a given origin with lower carbon emissions than by truckload transportation.

Recall that the carbon footprint of a truckload shipment is calculated using the following equation:

$$CF_{TL} = (d_{otr} + d_{ae}) \times c_{tl} \tag{6.8}$$

In this equation c_{tl} and d_{ae} are fixed quantities based on the operator's actual efficiencies. If we define $C_r(A) = d_{ae} \times c_{tl}$, $\omega_r = c_{tl}$, and $d_{otr} = \overline{AM}$ this equation becomes identical to the form used by Nierat (1997) to calculate the cost of truckload shipping.

Similarly, the carbon footprint of an intermodal shipment is calculated by:

$$C_{IM} = d_{od} \times c_d + d_r \times c_r + d_{dd} \times c_d \tag{6.9}$$

By defining $C_i(B) = d_{od} \times c_d + d_r \times c_r$, $\overline{BM} = d_{dd}$, and $\omega_i = c_d$ this expression also becomes identical to the one used by Nierat for the cost of intermodal shipping. With those substitutions in place we can then rewrite the equation in the following form to describe the carbon market area for terminal B:

$$d_{otr} - \frac{c_d}{c_{tl}} d_{dd} = \frac{d_{od} \times c_d + d_r \times c_r - d_{ae} \times c_{tl}}{c_{tl}} \tag{6.10}$$

By simplifying the calculation of the over the road distances as $d_{otr} = d_{gc} \times c$, where d_{gc} is the great circle distance between the origin and destination and c is the average road circuity factor, this produces an oval region oriented along the line from the origin to the destination terminal. The carbon market area then provides an explanation for why the carbon efficiency of intermodal shipments varies on a lane-by-lane basis. For any given origin location only destinations that fall within the carbon market area of a terminal will produce lower emissions than truckload transportation. The use of an overall average fails to capture the location dynamics that affect the actual efficiency. Given the difficulty in accurately estimating emissions from intermodal shipping, even when an overall average efficiency is known, this represents an opportunity for operators to provide a service to shippers through their knowledge of the network. By applying the carbon market area theory, intermodal operators can help shippers identify which lanes should be switched to intermodal.

The operator can then calculate not just the candidate locations, but the magnitude of the potential savings as well. The magnitude of the savings is necessary in order for shippers to properly balance the carbon footprint of the shipment with the other criteria of the decision, such as the cost, transit time, and service level. At any point within the market area the reduction in the carbon footprint is given by:

$$CF_{TL} - CF_{IM} = ((d_{otr} + d_{ae}) \times c_{tl}) - (d_{od} \times c_d + d_r \times c_r + d_{dd} \times c_d) \qquad (6.11)$$

Viewing the potential savings from overhead as contour lines surrounding the destination terminal we get a shape like that shown in Figure 6-6. The origin and destination terminal are shown in the x-y plane with the East-West position plotted on the x-axis and the North-South position on the y-axis. The oval surrounding the terminal represents the carbon market area where emissions from intermodal are lower than those of trucking. The potential savings from intermodal increase as we move closer to the terminal, and the contour lines mark the regions with savings corresponding to 200, 400, and 600 kg CO_2.

Plotted in the x-y plane with the magnitude of the savings along the z-axis this produces the shape shown in Figure 6-7 for the carbon market area. The savings peak at the location of the destination terminal, and decrease as the destination moves away from the terminal. The savings decrease at a higher rate as the destination moves closer to the origin location.

The shape is the result of the intersection of two cones. The first, giving the carbon footprint associated with a truckload shipment, takes on a minimum value of $C_r(A) = d_{ae} \times c_{tl}$ at A, the shipment origin, and increases with a slope of as c_{tl} the destination moves away from the origin. The second cone, giving the carbon footprint of the intermodal shipment, takes on a minimum of $C_i(B) = d_{od} \times c_d + d_r \times c_r$ at B, the destination terminal, and increases with slope c_d as the final destination moves away from the terminal. Viewed in cross section along the line between A and B, the difference between the two cones represents the savings from an intermodal switch, and is shown in Figure 6-8. Thus, the market area approach accounts for not just the distance of the shipment, but also the direction of travel in relation to the shipment origin and the intermodal ramps. This differs from other attempts to gauge the competitiveness of intermodal, such as the break-even approach used by Morlok and Spasovic

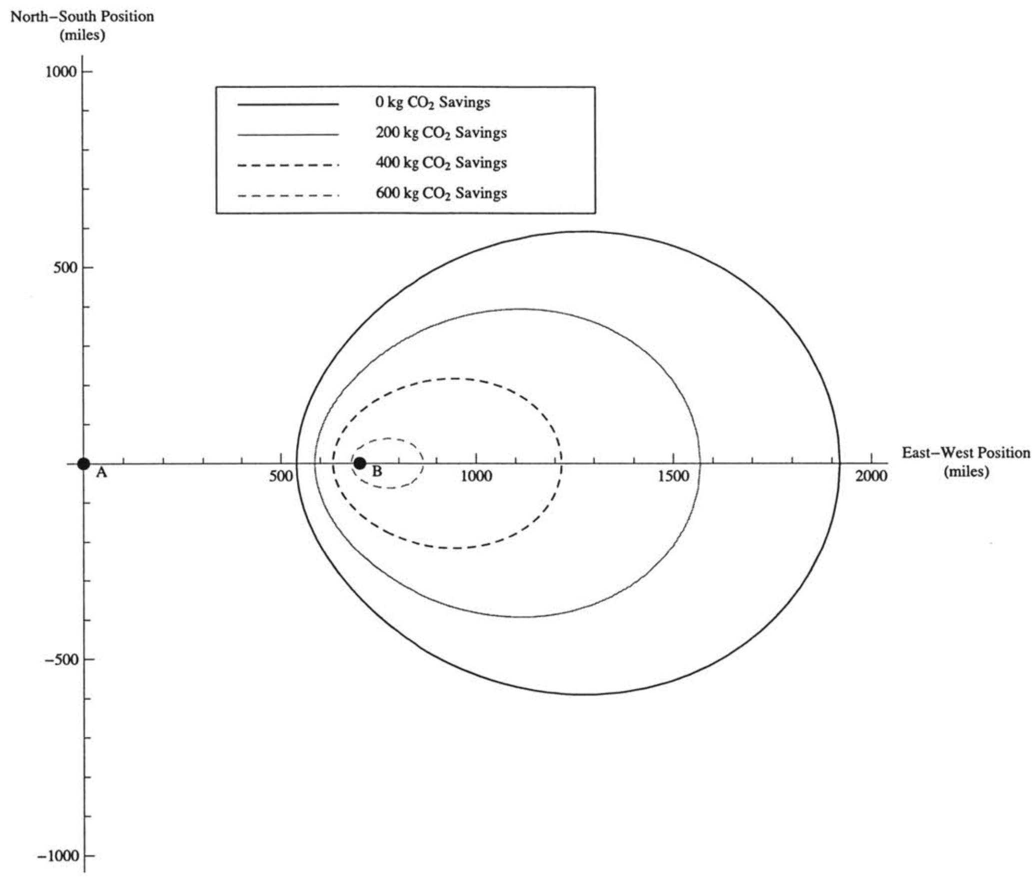


Figure 6-6: Overhead View of Intermodal Market Area

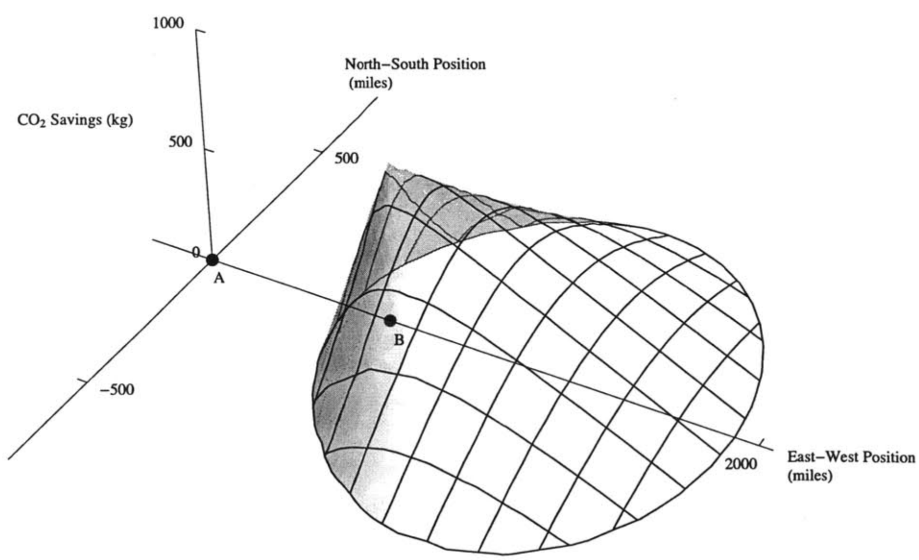


Figure 6-7: Three Dimensional View of Carbon Savings

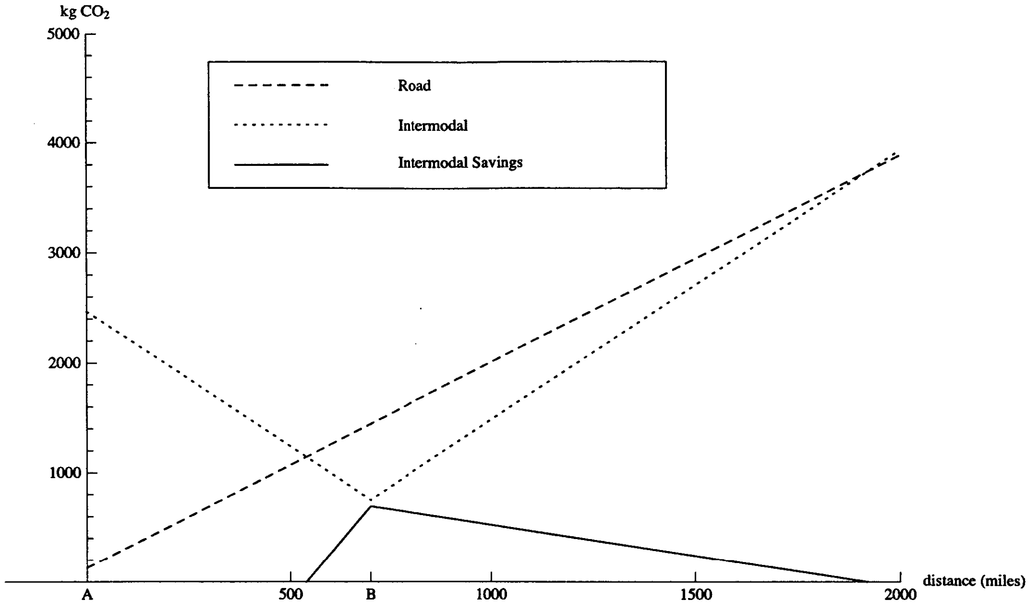


Figure 6-8: Cross Sectional View of Carbon Savings

(1995), which assumes there is some break-even distance above which all shipments sent by intermodal will be lower in cost than truckload. Some destinations may be impractical to serve by intermodal, even if the shipment distance is above the break-even distance, if there is no intermodal terminal nearby. The market area approach allows for the structure of the rail and intermodal network to be considered when evaluating shipping decisions.

Limbourg and Jourquin (2010) applied the intermodal market area concept to a hub and spoke network design problem, noting that a single terminal may have several overlapping market areas for shipments originating from different locations. Applying a similar idea, we examine the case of a single origin having multiple market areas around various destination terminals. Consider a shipper needing to move goods from an origin facility to a network of distribution locations. With the origin fixed the intermodal operator can determine the carbon market area for all of the possible destination terminal locations. Each destination terminal will have a carbon market area of different size and orientation, or possibly no market area at all. By identifying destinations that fall within the carbon market area of a terminal, the operator can identify candidate locations for a switch from trucking to intermodal.

Evaluated across the entire intermodal network the operator is able to identify the potential savings for any destination by selecting the mode and terminal that produce the lowest emissions. An example is shown in Figure 6-9. In this figure we show the potential savings for a shipment originating at a terminal location in Los Angeles by evaluating a network of destination terminals. The threshold level of emissions required to reach each destination terminal from the origin is first calculated. Then the emissions required to reach a grid of destination points is calculated for intermodal shipments routed through each destination terminal, as well as a truckload shipment from the origin. The potential intermodal savings are calculated by finding the destination terminal that produces the lowest emissions to reach the final destination using an intermodal shipment, and this result is compared with the estimated truckload emissions. Finally, the map is created using ESRI's ArcMap GIS software and applying interpolation to estimate the savings for all areas of the map.

The figure demonstrates many of the results from the carbon market area concept. In general the savings tend to increase for destinations further from the origin, as the efficiency of the long rail haul increases the potential of intermodal. However, the savings are also dependent on the distance from the terminals and the direction of travel, giving rise to several distinct oval shaped regions of higher potential savings surrounding a terminal and oriented along the direction of travel. As the destination moves aways from the terminal the savings are reduced, even as the length of the journey may increase. A significant area in the Western portion of the United States does not fall within any carbon market area, due to the relatively short distance of the rail haul and the lack of nearby terminals.

This concept can be applied to multiple shipment origins, and in Figure 6-10 we see how the savings look for a shipment originating in Texas. The potential savings at any destination can be significantly different from that shown in Figure 6-9 due to the difference in origin location and length of rail haul. The areas of greatest potential savings now occur on both the West and East coast, while the region outside of any market area occurs in areas around Texas. Due to the shorter length of rail haul from an origin in Texas the magnitude of possible savings are also reduced, as no destination provides as much savings as can be obtained by using intermodal to ship from Los Angeles to the East coast.

Based on the idea of the carbon market area, we can see that the use of average efficiency

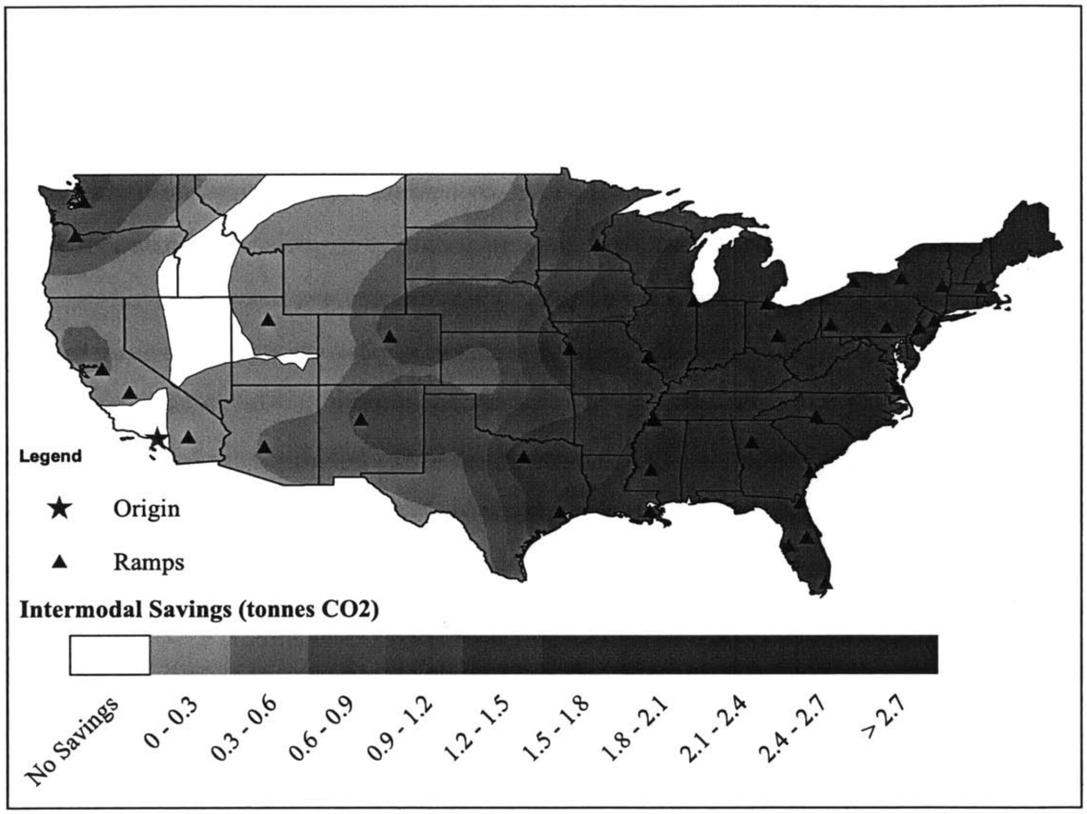


Figure 6-9: Potential Intermodal Carbon Savings from Los Angeles

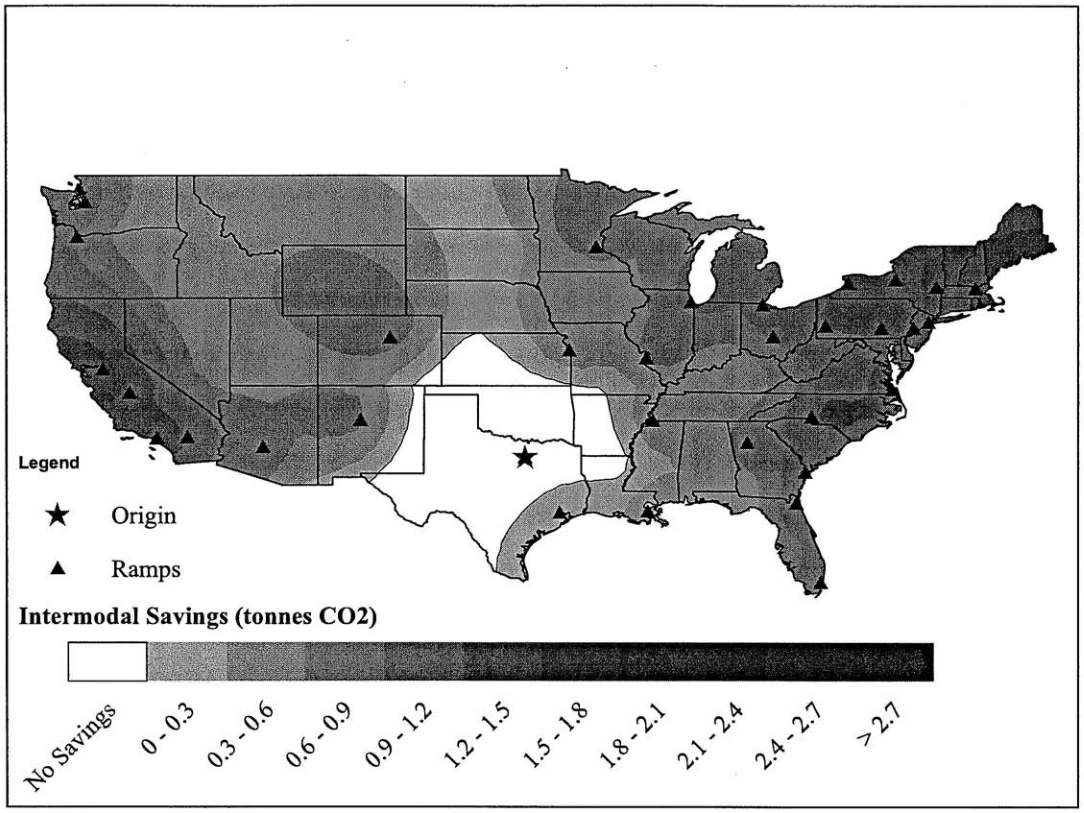


Figure 6-10: Potential Intermodal Carbon Savings from Texas

values can be misleading when choosing between modes of transport. The actual efficiencies are dependent on a number of factors, including the origin and destination locations, the relative efficiencies of different modes of travel, and the design of the intermodal network.

6.3.4 Discussion

In this section we presented a method for calculating the overall efficiency of intermodal in comparison to standard truckload transportation. Our results confirm the assumption that, on average, intermodal transport provides a service that can improve on the efficiency of truck transportation. The average carbon intensity of intermodal transport is estimated to be 70 g CO_2 per ton-mile, 44% lower than truckload. This estimate is lower than the range of 88-170 g CO_2/ton-mile based on the work of Vanek and Morlok (2000), but consistent with results from the IRU (2002) that show potential energy reductions of 20-50% compared to trucking. This methodology can have significant benefit to shippers looking to estimate their carbon footprint with limited information, as current standards provide little in the way of published data on intermodal efficiency. Our results show that a current publicly available calculator significantly underestimates the emissions from intermodal shipping in comparison to the actual efficiency achieved by an operator.

We further expand the analysis on the competitiveness of intermodal shipping through the carbon market area concept. We show that intermodal shipping is more efficient than truckload only in a specific area surrounding an intermodal terminal, called the carbon market area. This result has implications for intermodal operators in a number of ways. First, calculating the actual emissions from intermodal shipping is difficult without direct knowledge of the underlying rail and road network. Our results show that actual carbon intensity of intermodal shipping varies from 29 to 308 g CO_2/ton-mile depending on the lane under consideration. This represents an opportunity for intermodal operators to use their knowledge of the system to assist shippers in identifying lanes for a potential shift from truckload to intermodal. Providing detailed information regarding the potential savings can serve as a value added service, and may be useful in growing their intermodal business.

Second, by including the benefits of reduced greenhouse gas emissions the overall attractiveness of intermodal as a shipping mode can be increased. Fuller, Robinson, Fraire, and

Vadali (2011) provide an example of this when looking at the viability of a new intermodal terminal located in West Texas. Their results show the addition of the terminal has not just a financial benefit, but also an environmental benefit through reduced GHG emissions. When the positive benefits of the emissions reductions are included the overall attractiveness of intermodal as a mode is increased. This has a number of possible implications for other work on intermodal transportation, particularly in the area of terminal locations. Limbourg and Jourquin (2010) previously applied the market area concept to a terminal location problem, noting that traditional methods have failed to account for the actual shape of the market area by assuming a simple circular area. As seen in Figure 6-10 and Figure 6-9 the same principle applies to emissions, as the carbon savings vary not just based on distance from terminals, but also the direction of travel. Thus, the carbon market area concept helps identify regions where additional terminals have the greatest possibility of reducing emissions.

The use of the carbon market area concept illustrates the deficiencies in current estimates of mode carbon intensities. The average intensities provide a simple guideline that are sufficient for the traditional mode selection decision, but not the decision within the integrated supply chain. In order to correctly evaluate which lanes are suitable for a switch to intermodal the shipper needs to know the actual savings, and balance these characteristics with other considerations. The market area concept was originally developed for cost considerations, and we have extended it to consider CO_2 emissions. By providing both the cost and the CO_2 together the operator can provide the shipper with the information necessary to make the necessary tradeoff, given the shipper's willingness to pay for CO_2 reductions. In the next section we show that a similar lack of precision exists at the level of the carrier selection decision, and we show how shippers can explicitly consider the tradeoff between cost and CO_2 in their procurement decision.

6.4 Carrier Selection

A number of proposals for reducing the impacts of transportation have been suggested, focusing on changing logistical structures (Aronsson and Brodin, 2006). While some aspects, such as consolidation, packaging reduction, and product redesign are typically proposed, the subject of carrier selection has received less attention. In a review of the literature, Aronsson and Brodin (2006) identify only Wu and Dunn (1995) as a source that proposed carrier selection as a method of reducing environmental impact. Meixell and Norbis (2008) found that while companies and consumers cited the environment as an issue it was not discussed in their review of the literature on mode and carrier selection. Wu and Dunn (1995) cite quality certification, such as the example of the Chemicals Manufacturers Association certifying a carrier for using safe and environmentally responsible measures when transporting chemicals, as a system that will grow in popularity. Despite the lack of attention in the carrier selection literature, the use of carrier certification has become popular in practice through the work of the EPA's SmartWay partnership.

6.4.1 EPA SmartWay Program

The EPA's SmartWay transport program is a public-private partnership started in 2004 designed to improve the environmental performance of freight operations (EPA, 2012a). The program has undergone rapid growth since its inception. In a span of five years it grew to more than 1,400 partners (Tan and Blanco, 2009) and currently boasts nearly 3,000 partners (EPA, 2012b). SmartWay transport partners commit to reducing the environmental impact of their operations. Partners are allowed to use the SmartWay logo in marketing and communications materials, and the program offers a certification program that allows the use of a certified SmartWay logo for display on tractors and trucks. In addition, the EPA provides technology assistance, financing, and performance measurement tools (EPA, 2012a).

The EPA provides truckload carriers with a tool designed to capture fleet activity, benchmark performance, and track annual changes in performance. After completing the tool and having their submission approved by the EPA, the carrier is listed as a transport partner and appears in the database of SmartWay carriers used by shippers. Carriers that meet the highest standards of environmental performance and fuel efficiency are eligible for the SmartWay Excellence Award (EPA, 2012e). Each carrier is scored based on their performance on CO_2, NO_x, PM_{10}, and $PM_{2.5}$ per mile and per ton-mile. The carriers are placed in one of five bins with carriers of similar performance, and each carrier in the bin is assigned a score based on the midpoint performance of the bin. In this way the exact company data is not shared with competitors or customers, but performance can be determined to be somewhere within the range for the bin (EPA, 2012d).

A tool is provided for SmartWay shipper partners as well. The shipper tool captures performance based on the list of carriers used by the shipper. Data on the amount and type of transportation service provided by each carrier is entered. The tool imports the scores for the carriers, and overall performance is calculated based on a weighted average of the carrier scores. In addition the percentage of SmartWay carriers used is calculated and used to determine eligibility for use of the SmartWay logo (EPA, 2012c).

The program is designed in a way that encourages shippers to make use of high scoring SmartWay carriers. This creates incentive for the carriers to participate in the program, measure their greenhouse gas emissions, share the results with the shippers, and work to lower their emissions in order to win business from participating shippers. As shippers place more value on reducing emissions, the incentive for carriers to participate and lower emissions is increased. The pressure from shippers is one of the main contributing factors to the growth of the program (Tan and Blanco, 2009).

The current program focuses on calculating an average score for each carrier on a per mile basis. The carriers are separated into ten different groups based on performance, and shippers are allowed to see which performance group each carrier belongs to, along with the average CO_2 per mile for that performance group. This average score is useful for shippers to compare between different carriers, corresponding to the third step in the traditional transportation procurement process. However, using only an average score does not properly account for variations within each carrier's operations, variations that are taken advantage of in more sophisticated procurement strategies, such as combinatorial auctions.

6.4.2 Truckload Procurement Auctions

One of the first instances of an optimization based truckload auction process was implemented by Reynolds Metals Company in 1988 (Moore Jr, Warmke, and Gorban, 1991). Their implementation of a centralized dispatch system produced annual freight cost saving of $7 million, improved service quality, and established longterm relationships with top quality carriers. Sears Logistics Services implemented the first combined value auction in 1992 and reduced costs by 13%. The auction replaced the previous practice of bilateral negotiations with carriers for service on individual lanes (Ledyard, Olson, Porter, Swanson, and Torma, 2002). Elmaghraby and Keskinocak (2004) describe the use of a combinatorial auction run by Home Depot. The system allowed carriers to submit bids for packages of lanes, rather than the previous practice of accepting only bids for individual lanes. The process resulted in reduced rates for Home Depot and improved satisfaction by carriers. De Vries and Vohra (2003) report that by 2000 Logistics.com had contracted more than $5 billion in transportation through its software by Ford, Wal-Mart, and K-Mart.

Combinatorial auctions deliver benefits over traditional bid processes by allowing carriers to take advantage of economies of scope. Economies of scope exist when it is cheaper for one carrier to serve a set of lanes than if multiple carriers served those same lanes (Caplice, 1996). The main obstacle for shippers to achieve efficient allocation of lanes is hedging by the carriers. This hedging is due to two primary factors: information quality and network imbalance (Caplice and Sheffi, 2003). By balancing the loads in their networks, carriers can reduce costs by improving utilization of their fleets and maintaining their fleets at regular location, enabling drivers to return home regularly and predictably (Sheffi, 2004).

In a lane-by-lane procurement system, a carrier must bid for a lane while making assumptions regarding whether it will win business on other lanes. Since they are not assured of winning business on other lanes they can not guarantee economies of scope, and so they must hedge the price they are willing to bid to account for the possibility of not winning complementary lanes. Combinatorial auctions reduce the incentive for carriers to hedge their bids by allowing bidding on packages of lanes, thus carriers can bid for a complementary set of lanes together without the need to hedge against the possibility of winning only a portion of the lanes (Caplice and Sheffi, 2003).

6.4.3 Shipper Perspective

Caplice and Sheffi (2003) describe the auction process as being composed of three steps:

1. Bid Preparation – where the shipper determines what is to be bid out, what carriers to invite, how to present or package the business to be bid, and what opportunities

exist for different types of shipper-carrier relationships.

2. Bid Execution – where the shipper communicates the bid information to the carrier(s) and the carriers respond back with quotes. This exchange can differ in terms of bid visibility, number of rounds, and other more standard auction rules.

3. Bid Analysis and Assignment – where the shipper analyzes the carriers' responses, considers the business needs, and assigns the business to specific carriers.

The choices regarding these steps can produce a number of different formats for the auction. De Vries and Vohra (2003) and Abrache, Crainic, Gendreau, and Rekik (2007) provide several examples of structures for combinatorial auctions. Caplice (1996), Caplice and Sheffi (2003), Guo, Lim, Rodrigues, and Zhu (2005), and Chen, AhmadBeygi, Cohn, Beil, and Sinha (2009) provide specific instances for use with truckload transportation auctions. We are primarily considered with the Bid Analysis and Assignment process, and how carbon emissions can be incorporated into this decision. Caplice and Sheffi (2006) provide a review of a number of formulations of the carrier assignment problem that allow for different constraints and package types. We consider the most basic formation provided that allows for simple bids with no side constraints. The formulation is provided as follows:

$$\min \sum_{c} \sum_{k} \sum_{i,j} {}_{c}c^{k}_{i,j} \, {}_{c}x^{k}_{i,j} \tag{6.12}$$

subject to:

$$\sum_{c} \sum_{k} {}_{c}x^{k}_{i,j} = x_{i,j} \ \forall i, j$$

$${}_{c}x^{k}_{i,j} \geq 0 \ \forall i, j, c, k$$

where:

Indices

i	Shipping origin region
j	Shipping destination region
k	Bid package identification

c	Carrier identification

Decision Variables

${}_c x^k_{i,j}$	number of loads per time unit on lane i to j, assigned to carrier $c$under package k

Data

$x_{i,j}$	Volume of loads from shipper s, on lane i to j, that are being bid out
${}_c c^k_{i,j}$	Bid price per load on lane i to j, for carrier c as part of conditional bid k

This formulation minimizes total cost to the shipper while assuring that each lane is covered. While only simple bids are allowed, the carriers may submit multiple bids on a lane at different price levels to reflect differences in service levels, equipment, or other characteristics (Caplice and Sheffi, 2006). Other formulations allow for more complex bid packages and constraints, but for the purpose of incorporating the carbon footprint of carriers into the decision the simple formulation allows for sufficient detail.

Carriers may have a number of additional non-price qualities that shippers take into account when making the assignment decision. Examples of these attributes include on-time performance, familiarity, availability of equipment, accessorial services, pick-up performance, and ease of doing business (Sheffi, 2004). Carriers may set a required level of service and limit the choice of carriers to only those that meet the minimum service level (Sheffi, 2004), a practice consistent with the traditional method of carrier assignment portrayed in Figure 6-2a. This does not properly allow the continuous trade off between cost and level of service, so in practice shippers can allow all carriers to bid and apply a modifier to the bid, then solve the resulting minimization problem using the modified bids (Sheffi, 2004). Buer and Pankratz (2010) propose a third method to explicitly include quality in the model through a bi-objective optimization problem. Their approach produces a range of possible solutions, which the shipper must then evaluate to find their ideal balance of cost and quality.

The methods described by Sheffi (2004) and by Buer and Pankratz (2010) can incorporate carbon footprint considerations in a straightforward manner. In Buer and Pankratz (2010) the quality level at which the carrier fulfills the contract could simply be the total greenhouse gas emissions, and the second objective functions is changed to minimize emissions rather than maximize quality. The modifier approach, which we present here, can be represented by the following extension to the carrier assignment problem. Assume that ${}_cx^k_{i,j}$ consists of the modified bid price for bid package k from carrier c on the lane from i to j. The modified bid price incorporates the actual price of the bid along with all other qualities except the carbon footprint. Let ${}_ce^k_{i,j}$ be the carbon footprint for bid package k from carrier c on lane i to j in units of CO_2. Finally, let θ be the modifier applied to the carbon footprint based on the shipper's valuation of carbon given in terms of \$ per unit of CO_2. With these factors in place we can rewrite (6.12) as follows:

$$\min \sum_c \sum_k \sum_{i,j} \left({}_cc^k_{i,j} + \theta_c e^k_{i,j} \right) {}_cx^k_{i,j} \tag{6.13}$$

subject to:

$$\sum_c \sum_k {}_cx^k_{i,j} = x_{i,j} \ \forall i, j$$

$${}_cx^k_{i,j} \geq 0 \ \forall i, j, c, k$$

where:

Indices

i	Shipping origin region
j	Shipping destination region
k	Bid package identification
c	Carrier identification

Decision Variables

${}_cx^k_{i,j}$	number of loads per time unit on lane i to j, assigned to carrier c, under package k

Data

$x_{i,j}$ Volume of loads from shipper s, on lane i to j, that are being bid out

${}_{c}c^{k}_{i,j}$ Bid price per load on lane i to j, for carrier c, as part of conditional bid k

${}_{c}e^{k}_{i,j}$ Carbon footprint per load on lane i to j, for carrier c, as part of conditional bid k

In this formulation the shipper minimized total cost given their preference regarding the valuation on carbon emissions. If the shipper places no value on carbon then the problem simply reduces to the original formulation shown in (6.12). As the shipper's value on carbon increases carriers with a lower carbon footprint are rewarded with a smaller penalty modification to their bid than carriers with a higher carbon footprint. This allows for the continuous tradeoff between carbon performance and price, consistent with model of carrier assignment in an integrated supply chain shown in Figure 6-2b.

Inherent in this formulation is the idea that carriers provide the carbon footprint of their bid on a lane-by-lane basis, a level of precision not found in the current SmartWay program. While the SmartWay program does allow for the carbon footprint of each shipment to vary on a carrier-by-carrier basis, we noted previously that one advantage of the combinatorial auction process was the ability to leverage economies of scope to reduce the network imbalance issue. Since a major factor in reducing the network imbalance issues is reducing empty miles, this process should also help reduce the carbon footprint of the transportation service. Thus the factors that drive differences in prices between carriers and lanes should also drive differences in the carbon footprint, and this should be reflected in the bid process. This variation by lane due to network imbalance is common for other attributes as well (Sheffi, 2004). In the next section we discuss the problem of generating bids from the carrier's perspective, discuss the similarities between calculating cost and the carbon footprint, and provide a method for measuring the carbon footprint on a lane-by-lane basis.

6.4.4 Carrier Perspective

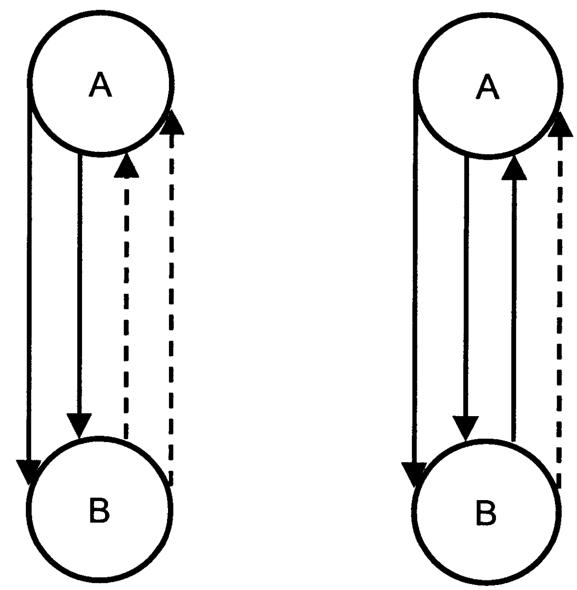
A number of strategies have been proposed for how carriers should develop bids for a combinatorial auction. Song and Regan (2003) provide the first method for generating carrier bids, constructing optimal tours given the carrier's current lane commitments and the lanes available for bid. The objective function minimizes either total cost or total empty cost and the output is the set of lanes the carrier should bid on and the total price for the bundled bid. While this process can provide the optimal set of bids, the exponential number of potential bids make it infeasible to implement in practice. Song and Regan (2005) provide an algorithm that provides bids that are manageable in size and competitive in quality through an optimization process designed to minimize empty miles. Lee, Kwon, and Ma (2007) attempt to create optimal tours that maximize profit given the ask price available on lanes and a cost per unit of distance. Chen et al. (2009) represent the cost of service on a lane as a combination of direct movement costs and repositioning costs. Direct movement costs are well understood by the carrier and typically based on distance. Repositioning costs are based on the movements required to obtain the next load, and are typically not known at the time of the auction.

Using this concept of direct costs and repositioning costs, we define the carbon footprint of any shipment to be composed of the emissions produced during the direct movement of the goods from origin to destination plus the emissions resulting from the empty repositioning movement required to secure the next load. The direct emissions are a known quantity based on, d_{ij}, the distance between the origin and destination, and c_l, the carbon intensity of the vehicle when loaded. Let the direct emissions, ${}_de_{ij}$, associated with the lane from i to j be:

$$ {}_de_{ij} = d_{ij} \times c_l \tag{6.14} $$

Similarly, let the emissions related to the repositioning cost required to move an empty vehicle from j to k, ${}_re_{jk}$, be given by (6.15), where d_{jk} is the distance from j to k and c_e is the carbon intensity of the vehicle when empty.

$$ {}_re_{jk} = d_{jk} \times c_e \tag{6.15} $$



(a) Empty Return (b) Loaded Return

Figure 6-11: Empty vs. Loaded Return

The outcome of most carrier models are a bundle of bids that consist of the lanes to bid on and the total cost of the bundle, based on sets of vehicle tours. The vehicle tours may consist of the carrier's current lane commitments as well as the lanes being bid on, while the cost represents the additional cost of servicing the new lanes. If we use (6.14) and (6.15) to calculate the carbon footprint of the bundle, we will get the emissions required to serve the lanes being bid on. This may have an undesirable result in practice. Consider the scenario provided by Ozener and Ergun (2008) shown in Figure 6-11a. A carrier currently is committed to two trips from A to B, and incurs two empty return trips. Assuming a distance of one between A and B, the current emissions produced serving the lanes is $2c_l + 2c_e$. If a single trip from B to A is available for bid the optimal tour will be constructed by replacing an empty trip from B to A with the loaded trip shown in Figure 6-11b. The new system carbon footprint will be $3c_l + c_e$ and the appropriate emissions cost for the bid will be the increase required for serving the new lane, $c_l - c_e$. The net result is the calculated carbon footprint to be bid on the new lane is less than the actual emissions produced by the vehicle driving from B to A.

If we impose a rule that the emissions must be at least equal to the direct emissions cost required to serve the new lanes the problem becomes one of simply allocating emissions from the empty movements to the lanes served by the carrier. Unfortunately, enforcing this constraint, known as the minimum liability constraint, on the direct emissions it is not possible to guarantee all emissions can be allocated in a manner that is both budget balancing, assuring that all emissions are allocated, and acceptable to all parties (Ozener and Ergun, 2008). Thus, even under deterministic conditions there is not an ideal method to calculate the carbon footprint of a given lane. However, our goal in calculating emissions at the lane level is not simply to provide an accounting method of assigning carbon emissions to the shippers, but also to estimate the future emissions for use in the procurement decision.

In practice the calculation of the direct emissions is straightforward, but calculating the emissions from repositioning is not. The exact repositioning movement is not likely to be known with certainty at the time of the auction (Chen et al., 2009). Because the act of moving a load from A to B removes a vehicle from A and adds one to B, there is an opportunity cost associated with the move. Figliozzi, Mahmassani, and Jaillet (2006) refer to methods that attempt to estimate the opportunity cost associated with the change in position of the vehicle from A to B as one step look ahead methods, and use a simulation method to estimate the costs given a distribution of load arrivals. Powell, Sheffi, Nickerson, Butterbaugh, and Atherton (1988) use a post-optimality method to calculate the opportunity costs of one more or less vehicle at a given node at a given time. Caplice and Sheffi (2006) use a simple method based on historical revenues in and out of nodes to calculate the costs, referred to as node potentials. Chen et al. (2009) represent the repositioning cost as a tiered step function based on current lane commitments, partial connections to other nodes with lane commitments, spot market opportunities, and finally empty movements back to the origin.

We propose a straightforward method, similar to Caplice and Sheffi (2006), to estimate the emissions associated with vehicle repositioning based on historical data. Consider the scenario for a specific movement from i to j shown in Figure 6-12. The load is first moved from the origin to destination, incurring the direct cost. After arriving at j the vehicle will be dispatched to some location k to pick up the next load, incurring the repositioning cost. However, at the time of the procurement of the shipment from i to j the actual routing of

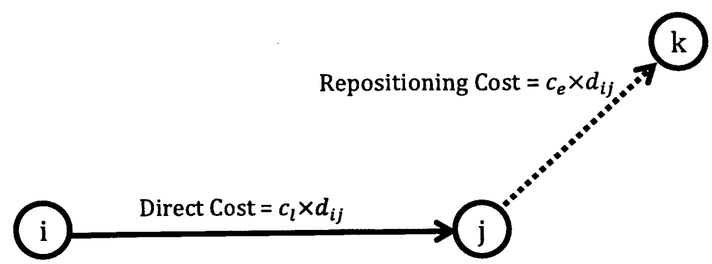


Figure 6-12: Direct and Repositioning Costs

the vehicle after arriving at j is likely to be unknown. Since the actual routing can not be used, we instead propose to use the *expected repositioning cost.*

6.4.5 Expected Repositioning Cost Approach

The expected repositioning cost for a given node is simply the average repositioning cost incurred for all shipments with that node as the destination. Consider the situation shown in Figure 6-13. In addition to the original shipment from i to j we have two other shipments arriving at j in the same time period. After arriving at j the vehicles will be dispatched to three different locations, each incurring a different repositioning cost due to differences in distance to the respective destinations. From a system perspective the actual routing is arbitrary, as total system costs are fixed. By allocating costs from a specific repositioning movement to a lane, the cost for that lane becomes dependent on the routing chosen, even though actual system costs are independent of that choice. If we instead use the average repositioning distance the actual choice of dispatch is irrelevant, and only the total routing distance is considered.

We define the expected repositioning cost, ${}_r e_{ij}$, for any shipment from i to j by:

$$ {}_r e_{ij} = d_j \times c_e \qquad (6.16)$$

where d_j is the expected repositioning distance for a shipment terminating at j and c_e is the carbon intensity of an empty truck. The expected repositioning distance can be calculated

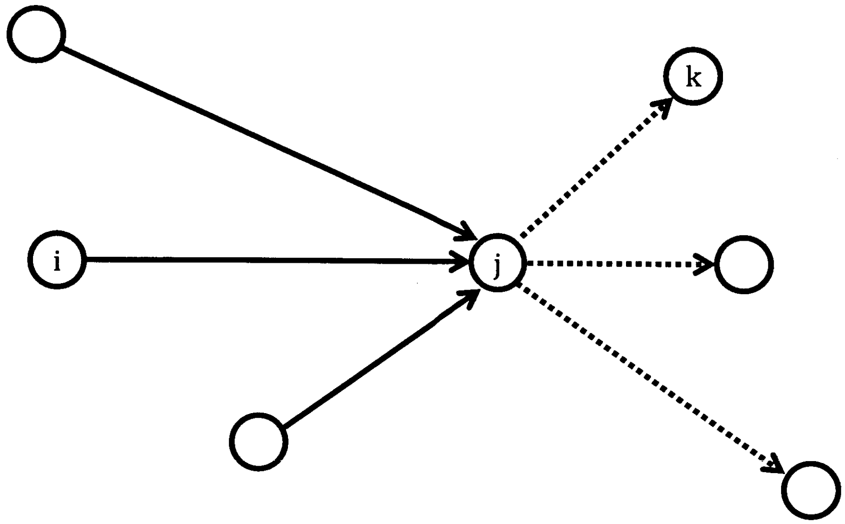


Figure 6-13: Expected Repositioning Costs

as:

$$d_j = \frac{\sum_i \sum_k {}_k d_{ij}}{|j|} \tag{6.17}$$

where:

${}_k d_{ij}$ =repositioning distance of the kth shipment from i to j

$|j|$ =total number of shipments with destination j

We can now define the estimated carbon footprint for any given lane from i to j as follows:

$$e_{ij} = {}_d e_{ij} + {}_r e_{ij} = d_{ij} \times c_l + d_j \times c_e \tag{6.18a}$$

$$= d_{ij} \times c_l + d_j \times c_e \tag{6.18b}$$

where:

d_{ij} =distance from i to j

d_j =expected repositioning distance for node j

c_l =carbon efficiency of a loaded vehicle

c_e =carbon efficiency of an empty vehicle

In order to understand how this works in practice we collected data from a national truckload carrier for all truckload movements made during a six month time period. This data included the origin, destination, and repositioning distance for more than 100,000 longhaul (greater than 500 miles) truckload shipments. In addition the carrier supplied their estimated values of c_l and c_e based on their operating data. Using this data set we computed the carrier's SmartWay score, e_{sw}, using the following method:

$$e_{sw} = \frac{\sum_i \sum_j \sum_k (d_{ij} \times c_l + {}_k d_{ij} \times c_e)}{\sum_i \sum_j \sum_k d_{ij}} \tag{6.19}$$

where:

d_{ij} =distance from i to j

${}_k d_{ij}$ =empty repositioning distance for the k^{th} shipment from i to j

c_l =carbon efficiency of a loaded vehicle

c_e =carbon efficiency of an empty vehicle

This value is expressed in grams of CO_2 per mile. The coefficient represents the total carbon emitted during all movements, both loaded and empty, while the denominator represents the total loaded miles of travel. This value was compared to the carrier's actual reported SmartWay score, calculated using fuel purchase receipts rather than estimated efficiencies, and was found to be within 1% of that value. Using this value the carbon footprint for any shipment on a given lane can be calculated by multiplying e_{sw} by d_{ij}. This represents a baseline estimated CO_2 that a shipper would associate with a given carrier on that lane if it were to use the carrier's SmartWay score.

Count	13118	Coefficient of Variation	0.04
Mean	1.85	Median	1.84
Standard Deviation	0.08	Percentile 25% (Q1)	1.80
Minimum	1.72	Percentile 75% (Q2)	1.90
Maximum	2.45	MAD	0.05

Table 6.5: Lane Statistics

We then calculated the carbon footprint using (6.18a) on a lane-by-lane basis. To lessen the effect of any outlier shipments all lanes were aggregated at the three digit zip code level, and any lane with less than five shipments was eliminated from the analysis. The remaining data set consisted of over 97,000 shipments across more than 13,000 lanes. The relative carbon intensity on each lane was calculated by dividing the carbon footprint of the lane by its distance to get a measure that could be compared with the SmartWay value of 1.83 kg of CO_2 per mile. A summary of the results is shown in Table 6.5.

When viewed on a lane-by-lane basis the mean and median lane efficiencies are close to the overall SmartWay score. However, nearly 15% of the lanes show more than a 10% difference above or below this value, with values at the high end showing up to a 35% error in estimated carbon emissions. A histogram showing the distribution of the carbon intensity parameter is shown in Figure 6-14. The dashed vertical line shows the average performance level of the carrier using the SmartWay score.

While the average deviation on any lane is nearly 5%, the possible error could be greater when the range of carriers is included. Consider two carriers, A and B, that each submits a bid on a lane that is equal in financial cost and carbon footprint using their SmartWay score. In this case the shipper would be indifferent between the carriers, and either bid could be accepted. However, given the possible deviation in the lane-level carbon footprint calculations, the bids could be considerably different in practice. If the lane is one where Carrier A emits below average levels of CO_2 and Carrier B emits above average, the error can be compounded.

Further, while the error in carbon estimated may not be significant from the shipper's perspective, the range of values within one carrier's performance by lane is similar to performance between different carriers. If the difference in performance between carriers is

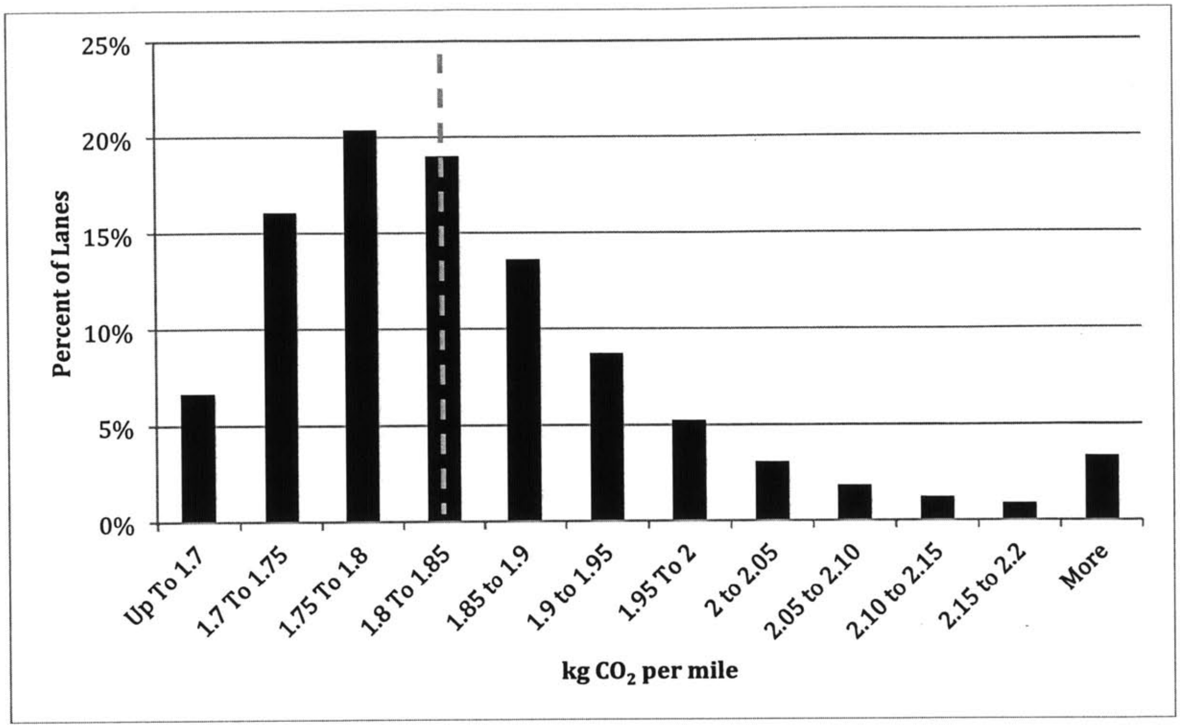


Figure 6-14: Distribution of Carbon Intensity by Lane

Count	64	Coefficient of Variation	0.098
Mean	1.97	Median	1.92
Standard Deviation	0.192	Percentile 25% (Q1)	1.84
Minimum	1.71	Percentile 75% (Q2)	2.07
Maximum	2.54	MAD	0.114

Table 6.6: Carrier Statistics

significant enough to account for in the procurement process then the lane-level variations within carrier's performance should also be accounted for. Using data obtained from the results of a shipper's truckload auction we can see the reported SmartWay score of the 64 carriers that participated in the auction. A summary of statistics for these carriers is shown in Table 6.6.

When viewing the distribution of carriers we can see that a SmartWay score of 1.83 would place the carrier near the top 25% of participating carriers. However, when taking into account the distribution at the lane level we can see that on nearly 20% of its lanes the carrier would be similar to or better than the highest rated carrier's average score. Likewise,

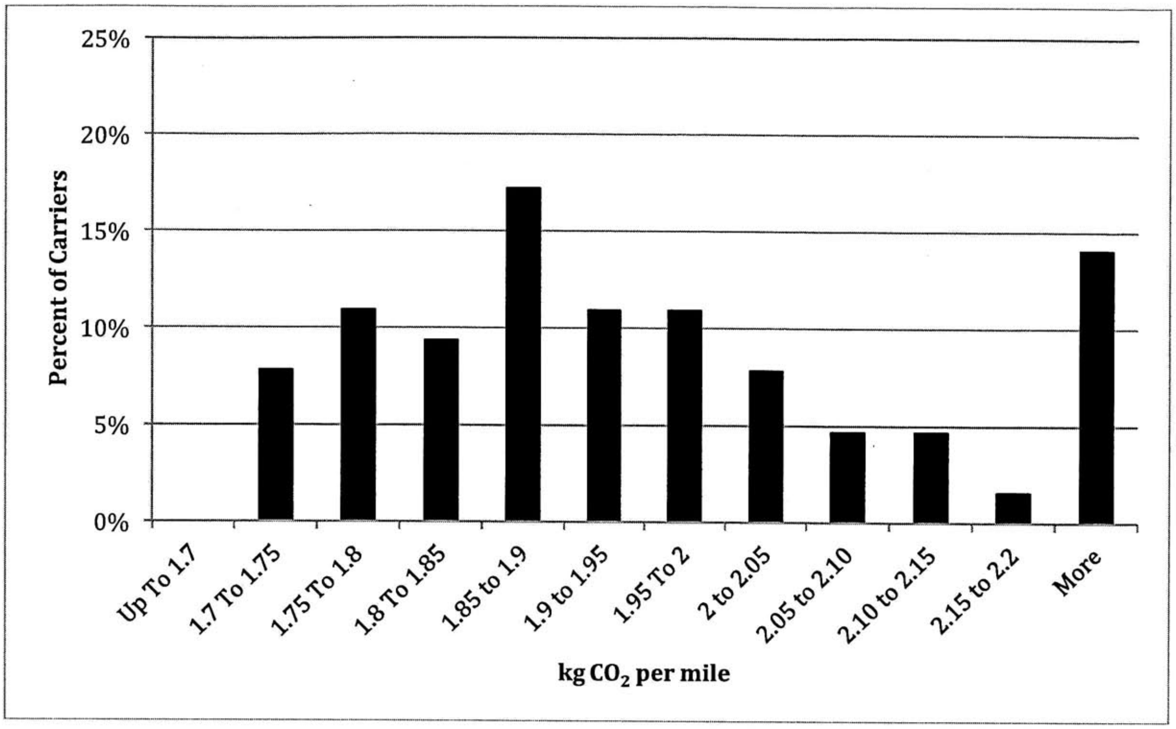


Figure 6-15: Distribution of Average Carbon Intensity by Carrier

on about 5% of lanes the carrier would rank in the bottom quartile.

6.4.6 Discussion

In this section we have presented a method for carriers to develop lane-level carbon metrics that shippers can incorporate in combinatorial auctions. This work contributes to the ability of shippers to improve the carbon efficiency of the supply chain in several ways. First, the use of carrier selection as a method for improving environmental performance has received little attention in research, despite the popularity within industry. We show how the combinatorial auction process provides an opportunity for carriers to take advantage of economies of scope, which can create a benefit by reducing empty miles and lowering greenhouse gas emissions. We have presented a method for shippers to extend the auction mechanism to account for carbon emissions in a way that allows them to trade off the value of carbon reductions against other service considerations. Finally, we present a method for carriers to estimate their carbon emissions on a lane-by-lane basis suitable for use in procurement auctions.

This is an important consideration, as the network imbalances that lead to differences in the cost to service lanes directly affect the emissions produced on those lanes. When the procurement decision is being made at the lane-level the carbon should be accounted for at a similar level of precision. Not taking the variation between lanes into account can lead not only to incorrect decisions in the outcome of the auction process, but also forgoes savings that could have been obtained. Our results show that the variation within a single carrier's lane-by-lane performance is similar to that found in comparisons of average performance between carriers. Taking these variations into account has the potential to improve performance at the expense of only slightly more complicated carbon accounting.

6.5 Conclusions

In this chapter we have proposed the use of an Activity Based Costing system as a method for firms to calculate the carbon footprint of their products in a way that supports improved decisions within the supply chain. Through an analysis of the transportation decision we have shown that current programs designed to calculate carbon emissions lack the necessary precision to support decisions within an integrated supply chain. We have proposed methods for both intermodal and truckload transportation that improve on current programs and support the types of decisions shippers face. Inherent in our discussion is the idea that shippers care about carbon emissions and that carriers will be willing to share this information truthfully. Though organizations such as the EPA and GHG Protocol provide standards for measuring carbon emissions there is no guarantee that carriers will report these numbers truthfully. Without verification of these numbers shippers may be unwilling to pay a premium for carriers that report low carbon scores. In the next chapter we justify these assumptions through an analysis of the use of voluntary carbon labels in a model of vertically differentiated products. Our model explicitly accounts for additional costs required to verify and communicate carbon footprint data with customers.

Chapter 7

A Vertical Differentiation Model of Product Carbon Labels

In the previous chapter we showed how firms can share carbon footprint information with their customers in a way that allows for improved decision-making within the supply chain. The discussion assumes that firms are willing to do this because customers value reductions in carbon emissions. In this chapter we provide justification for this assumption by showing how voluntary disclosure of carbon footprint information can result in increased profits when consumers care about the environment.

7.1 Introduction

Product labels that disclose the carbon footprint of the product are emerging as a popular type of eco-label. The Carbon Trust's carbon label currently certifies more than $3 billion worth of products annually. This is primarily due to backing from major British retailer Tesco, which planned to put carbon labels on all 70,000 of its products (Economist, 2011). Despite this emergence there has been little work to understand the characteristics of carbon labels that differ from standard eco-labels. According to ISO standards there are three types of environmental labels (Fet and Skaar, 2006):

- Type I, which involve third party programs awarding labels claiming environmental preferability.

- Type II, which are based on self-labeled declarations.
- Type III, which make a claim about the product based on a Life Cycle Assessment with third party verification.

Under these criteria a carbon label is considered a Type III label, of which little research has been done. Much of the work instead focusing Type I labels, which are generally referred to as eco-labels (Gallastegui, 2002).

Previous work on the role of labels in improving environmental quality has shown that firms will overcomply with environmental regulations in order to attract environmentally aware consumers (Konishi, 2011). This is due to the evidence suggesting that at least some consumers are willing to pay a premium in order to "protect the environment" (Mason, 2011). This willingness to pay has been attributed to the idea of "warm glow" benefits introduced by Andreoni (1989). In the context of greenhouse gas emissions, when a firm reduces its level of emissions all consumers benefit from the public good, regardless of whether they buy products from that firm or not. However, some consumers may perceive a benefit when purchasing from that firm. This additional utility gained from the feeling of contributing to the public good is defined as the warm glow benefit (Andreoni, 1989).

In order to receive this benefit the consumer must know they are purchasing a product produced with lower emissions. However, the carbon footprint of a product is a credence attribute and not observable by consumers. When consumers are aware of the carbon footprint of products, firms can benefit from the warm glow effect by differentiating their products from competitors through a lower carbon footprint. This represents a type of vertical differentiation. Vertical differentiation occurs when products have different levels of some quality and all consumers prefer more of the quality to less of it. This is quality in the sense of some attribute of the product that consumers prefer. For example, the processing speed of a computer is a quality and, ignoring cost considerations, consumers prefer higher processing speed (more of the quality). This is in contrast to horizontal differentiation, where consumers may disagree about the best level of quality. To help understand why firms would be willing to reduce their carbon emissions and communicate this information to their customers, we examine the idea of a carbon label through a model of vertical product differentiation.

In Section 7.2 we provide a review of the literature on vertical differentiation models. In Section 7.3 we present a basic model of vertical differentiation in a duopoly setting. In Section 7.4 we extend the basic model to consider the use of a carbon label to inform consumers about the product's carbon footprint. In Section 7.5 we consider a different type of carbon label, based on a Type I, certification-style eco-label, which we refer to as a discrete label. In Section 7.6 we extend our basic carbon label in the context of a two-stage supply chain where the upstream supplier can also contribute to reductions in the carbon footprint. In Section 7.7 we conclude with a discussion of the results of our model in the context of some reason developments related to carbon labels.

7.2 Background

The concept of vertical differentiation was primarily developed through the work of Gabszewicz and Thisse (1979, 1980) and Shaked and Sutton (1982, 1983). Shaked and Sutton first introduced the two stage vertical differentiation model where quality was the decision variable.

In the basic model of vertical differentiation, as characterized by Tirole (1988), consumers are defined by a preference parameter θ distributed uniformly between a minimum and maximum value, $\theta \in [\underline{\theta}, \overline{\theta}]$. The consumer preference is described by utility $U = \theta s - p$ if a good of quality s is purchased at price p by a consumer that is willing to pay θ per unit of quality, and 0 otherwise. Production occurs at a constant marginal cost, which can be assumed to be 0 without loss of generality (Motta, 1993). Each consumer either purchases one unit of the good or none at all, and the total market size is assumed to be 1. There are two firms, and Firm i produces a good of quality s_i, with $s_2 > s_1$. The firms compete in a two-stage game where they compete first in quality and then in price.

Tirole assumes a "covered" market, one in which all consumers purchase one of the two goods, and that quality is costless. These assumptions produce the maximum differentiation possible, with Firm 2 setting its quality to the highest available and Firm 1 to the lowest available. This is due to the fact that increasing the differentiation between the products relaxes the price competition in the second stage and allows the firms to earn higher profits.

Since quality is costless, Firm 2 increases quality to the highest possible level to maximize the differentiation between the products.

A number of variations of this basic game have appeared in the literature. The variations differ primarily in their assumptions regarding the market, covered or uncovered, as well as the cost of quality. Choi and Shin (1992) used an identical model to Tirole, but assumed an uncovered market, producing a different quality choice for the low quality firm. Thus, the choice of covered or uncovered market can impact the results of the model. Wauthy (1996) showed that while many models assume a covered or uncovered market, the choice is in fact endogenous to the choices of the game and dependent on the range of consumer preferences. With fixed costs of quality Liao (2008) proved that the covered market with an interior solution is not an equilibrium, and that depending on consumer heterogeneity the outcome is either an uncovered market or a covered market with a corner solution. Therefore the choice of a covered or uncovered market is not an explicit decision, but rather an outcome of the choice of consumer heterogeneity.

The assumptions regarding the nature of the cost of improving quality can also affect the results of the model. Moorthy (1988) used a quadratic marginal cost of quality in order to have a tractable problem where the cost of quality increases faster than any consumer's willingness to pay. His results show a Nash equilibrium different from the maximum differentiation found in the case with no quality costs. The quadratic marginal cost assumption has been used in other work, including Rhee (1996); Villas-Boas (1998); and Desai (2001). Chambers, Kouvelis, and Semple (2006) consider a less restrictive requirement that the marginal cost be increasing and convex. Wang (2003) uses a cubic marginal cost to show that the higher quality firm does not always earn the higher profit when there is a variable cost to quality. Motta (1993) extended the use of variable quadratic costs to both Bertrand and Cournot competition.

A fixed cost of quality was used by Ronnen (1991) to show the existence of a unique Nash equilibrium under the assumption that the cost of quality is strictly convex. Though Ronnen also considered a variable cost when examining the effect of a minimum quality standard, those costs were assumed to be linear or concave and did not change the results from the fixed cost case. Motta (1993), Lehmann-Grube (1997), and Liao (2008) all assume a fixed cost of quality of quadratic form.

Using either a fixed or variable cost of quality produces similar results, and arguments exist for both forms. Crampes and Hollander (1995) chose a variable cost of quality, arguing that this is the more relevant case as quality standards in manufacturing pertain to materials and ingredients which impact variable costs more than fixed. Lehmann-Grube (1997) argues instead for the use of fixed costs. Since quality is assumed to be fixed in the first stage of the game it would be difficult for firms not to change quality when they incur variable costs in the second stage.

7.3 Basic Model

The game is played as a standard, non-cooperative two-stage game. In the first stage the firms simultaneously choose their level of quality. In the second stage the firms simultaneously set prices after observing both quality levels. Without loss of generality we set each firms' marginal cost to zero and designate Firm 1 the low quality firm and Firm 2 the high quality producer. Recognizing that some consumers may place little or no value on reductions in carbon emissions we set the market such that $\theta \in [0, \overline{\theta}]$. This means that the market will be uncovered, as at any positive price there will be some consumers that choose not to buy.

In keeping with the bulk of existing literature we measure quality such that higher is better. As a lower carbon footprint is actually preferred our measure of quality, s, can be thought of as the reduction in emissions of the product's carbon footprint. This is similar to the model used by Arora and Gangopadhyay (1995). See Moraga-Gonzalez and Padron-Fumero (2002) for an example of a vertical differentiation model based on the actual emissions produced. In our model at quality level $s = 0$ the product's carbon footprint is some amount of emissions e. By investing in new technology the firm reduces the carbon footprint from e to $e - s$ at a cost of $C(s)$. The individual consumer preferences can be thought of as their marginal willingness to pay for emissions reductions in terms of dollars per unit of carbon. A consumer of type θ would then be willing to pay up to θs additional dollars for a product with a carbon footprint of $e - s$ compared to the original product with a carbon footprint of e. We assume a quadratic fixed cost of quality improvement for each firm of the form

$C(s) = \alpha s^2$ with $\alpha > 0$.

Now that the rules of our game our specified, we can solve for the choices of quality and price by the firms. Our game is similar to that of Motta (1993), and our results follow from those shown in that work. We first note that there are two specific customers of interest, the one indifferent between the products of Firm 1 and Firm 2, and the one indifferent between the product of Firm 1 and no product at all. At given levels of quality, s_1 and s_2, and prices, p_1 and p_2, the consumer that is indifferent between the two products, noted by $\hat{\theta}_{12}$, is determined by setting the utility from purchasing each product equal to one another.

$$\hat{\theta}_{12} s_1 - p_1 = \hat{\theta}_{12} s_2 - p_2 \tag{7.1}$$

Solving 7.1 for $\hat{\theta}_{12}$ gives the consumer indifferent between the products as the one where:

$$\hat{\theta}_{12} = \frac{p_2 - p_1}{s_2 - s_1} \tag{7.2}$$

The consumer indifferent between the low quality product and no product at all is noted by $\hat{\theta}_{01}$ and is determined by setting the utility of purchasing the low quality product equal to 0.

$$\hat{\theta}_{01} s_1 - p_1 = 0 \tag{7.3}$$

Solving 7.3 for $\hat{\theta}_{01}$ gives the indifferent consumer as the one where:

$$\hat{\theta}_{01} = \frac{p_1}{s_1} \tag{7.4}$$

With these consumers identified we can determine the market share for each of the firms. All consumers with $\theta > \hat{\theta}_{12}$ choose the higher quality product, while those with $\hat{\theta}_{01} < \theta < \hat{\theta}_{12}$ choose the lower quality product. Consumers with $\theta < \hat{\theta}_{01}$ choose no product at all. Normalizing the total size of the market to 1 the quantities sold by each firm, q_1 and q_2, are given by:

$$q_1 = \frac{\hat{\theta}_{12} - \hat{\theta}_{01}}{\bar{\theta}} = \frac{1}{\bar{\theta}} \left(\frac{p_2 - p_1}{s_2 - s_1} - \frac{p_1}{s_1} \right) \tag{7.5}$$

$$q_2 = \frac{\bar{\theta} - \hat{\theta}_{12}}{\bar{\bar{\theta}}} = \frac{1}{\bar{\bar{\theta}}}\left(\bar{\theta} - \frac{p_2 - p_1}{s_2 - s_1}\right) \tag{7.6}$$

With these prices and qualities we can write the profit function for each firm as follows:

$$\Pi_1\left(p_1, p_2, s_1, s_2\right) = p_1 q_1 - \alpha s_1^2 = \frac{p_1}{\bar{\bar{\theta}}}\left(\frac{p_2 - p_1}{s_2 - s_1} - \frac{p_1}{s_1}\right) - \alpha s_1^2 \tag{7.7}$$

$$\Pi_2\left(p_1, p_2, s_1, s_2\right) = p_2 q_2 - \alpha s_2^2 = \frac{p_2}{\bar{\bar{\theta}}}\left(\bar{\theta} - \frac{p_2 - p_1}{s_2 - s_1}\right) - \alpha s_2^2 \tag{7.8}$$

We begin by solving the second stage of the game assuming the qualities have been fixed in the first stage to the values s_1 and s_2. To do this we maximize each firm's profit function with respect to its price, producing the following first order conditions:

$$\frac{\partial \Pi_1}{\partial p_1} = 0 \Rightarrow \frac{1}{\bar{\bar{\theta}}}\left(\frac{p_2 - p_1}{s_2 - s_1} - \frac{p_1}{s_1}\right) - \frac{p_1}{\bar{\bar{\theta}}}\left(\frac{1}{s_2 - s_1} + \frac{1}{s_1}\right) = 0 \tag{7.9}$$

$$\frac{\partial \Pi_2}{\partial p_2} = 0 \Rightarrow \frac{1}{\bar{\bar{\theta}}}\left(\bar{\theta} - \frac{p_2 - p_1}{s_2 - s_1}\right) - \frac{p_2}{\bar{\bar{\theta}}}\left(\frac{1}{s_2 - s_1}\right) = 0 \tag{7.10}$$

Solving the first order conditions produces the following optimal prices in response to the other firm's choice of quality and price:

$$p_1 = \frac{s_1 p_2}{2 s_2} \tag{7.11}$$

$$p_2 = \frac{p_1 + \bar{\theta}\left(s_2 - s_1\right)}{2} \tag{7.12}$$

To find each firm's best response function purely in terms of the quality choices we substitute 7.12 in to 7.11 and solve for p_1. This produces the following best response prices for both firms:

$$p_1 = \frac{\bar{\theta} s_1\left(s_2 - s_1\right)}{4 s_2 - s_1} \tag{7.13}$$

$$p_2 = \frac{2\bar{\theta} s_2\left(s_2 - s_1\right)}{4 s_2 - s_1} \tag{7.14}$$

Using these prices we can now write each firm's profit as a function of the quality choices:

$$\Pi_1(s_1, s_2) = \frac{\bar{\theta} s_1 s_2 (s_2 - s_1)}{(4s_2 - s_1)^2} - \alpha s_1^2 \tag{7.15}$$

$$\Pi_2(s_1, s_2) = \frac{4\bar{\theta} s_2^2 (s_2 - s_1)}{(4s_2 - s_1)^2} - \alpha s_2^2 \tag{7.16}$$

We can now solve for the quality choice of each firm in the first stage, anticipating the price competition in the second stage. Maximizing each profit function with respect to the firm's quality choice gives the following first order conditions:

$$\frac{\partial \Pi_1}{\partial s_1} = 0 \Rightarrow \frac{\bar{\theta} s_2^2 - 2\bar{\theta} s_1 s_2}{(4s_2 - s_1)^2} + \frac{2\bar{\theta} s_1 s_2 (s_2 - s_1)}{(4s_2 - s_1)^3} - 2\alpha s_1 = 0 \tag{7.17}$$

$$\frac{\partial \Pi_2}{\partial s_2} = 0 \Rightarrow \frac{12\bar{\theta} s_2^2 - 8\bar{\theta} s_1 s_2}{(4s_2 - s_1)^2} + \frac{32\bar{\theta} s_2^2 (s_2 - s_1)}{(4s_2 - s_1)^3} - 2\alpha s_2 = 0 \tag{7.18}$$

By moving the terms to the right hand side and simplifying the results we get the following expressions for s_1 and s_2:

$$s_1 = \frac{\bar{\theta} s_2^2 (4s_2 - 7s_1)}{2\alpha (4s_2 - s_1)^3} \tag{7.19}$$

$$s_2 = \frac{4\bar{\theta} s_2 (4s_2^2 - 3s_1 s_2 + 2s_1^2)}{2\alpha (4s_2 - s_1)^3} \tag{7.20}$$

There does not appear to be an easy analytical solution to these first order conditions. However, Motta (1993) showed that if we define a value μ such that $s_2 = \mu s_1$ with $\mu > 1$ there is exactly one possible real value for μ, $\mu = 5.2512$. Writing s_1 and s_2 in terms of μ we have:

$$s_1 = \frac{\bar{\theta} \mu^2 (4\mu - 7)}{2\alpha (4\mu - 1)^3} \tag{7.21}$$

$$s_2 = \frac{4\bar{\theta} \mu (4\mu^2 - 3\mu + 2)}{2\alpha (4\mu - 1)^3} \tag{7.22}$$

Finally, with the quality choices known we can now determine each firm's quality, quantity, price, and profit. Those results are summarized in Table 7.1. As shown in Lehmann-Grube (1997), this result is a Nash equilibrium where the higher quality firm earns the higher profit, and this high quality advantage holds for any sufficiently convex cost function.

Parameter	Firm 1	Firm 2
Price (p)	$\frac{\overline{\theta}^2 \mu^2 (4\mu-7)(\mu-1)}{2\alpha(4\mu-1)^4}$	$\frac{8\overline{\theta}^2 \mu(4\mu^2-3\mu+2)(\mu-1)}{2\alpha(4\mu-1)^4}$
Quality (s)	$\frac{\overline{\theta}\mu^2(4\mu-7)}{2\alpha(4\mu-1)^3}$	$\frac{4\overline{\theta}\mu(4\mu^2-3\mu+2)}{2\alpha(4\mu-1)^3}$
Quantity (q)	$\frac{\mu}{(4\mu-1)}$	$\frac{2\mu}{(4\mu-1)}$
Profits (Π)	$\frac{\overline{\theta}^2 \mu^3 (4\mu-7)(4\mu^2-3\mu+2)}{4\alpha(4\mu-1)^6}$	$\frac{16\overline{\theta}^2 \mu^3 (4\mu^2-3\mu+2)(4\mu-7)}{4\alpha(4\mu-1)^6}$

Table 7.1: Basic Vertical Differentiation Model

Though the high quality firm earns the larger profits, the low quality firm still earns profits above the undifferentiated case, where profits would be zero.

This demonstrates the basic intuition behind the vertical differentiation concept. A key requirement of such models is that consumers know the quality levels of both products, a requirement that is not met for credence attributes, like the carbon footprint, without some mechanism to inform consumers. In the next section we review various approaches to handling this issue and formulate an extension to our basic model that accounts for the need to communicate product quality through a labeling mechanism.

7.4 Carbon Label Model

A number of different models have been used to study labeling of credence attributes. Roe and Sheldon (2007) consider the issue of credence good labels under a variety of different labeling policies in a vertically differentiated scenario. Their labeling policy allows labels that can be either continuous or discrete values, allows voluntary or mandatory labeling, and includes a fixed cost of labeling. Ibanez and Grolleau (2008) suggest three criteria for deciphering an eco-label based on who defines the standard, how the claim is verified, and how it is signaled to customers. Baksi and Bose (2007) distinguish between claims that can be either self-labelled (Type II labels) or involve third party labeling (Type I).

Much of the work in the area of eco-labels have been focused on Type I or Type II labels that consider two discrete levels of quality, and examine different issues based on the structure of the label model. Baksi and Bose (2007) consider a model with binary levels for high and low quality products and consider the incentives of low quality firms to cheat by claiming high quality status. Bonroy and Constantatos (2008) consider the case of credence labels with two firms producing at different levels of quality where the high quality firm incurs a higher constant marginal cost per unit of production. The equilibrium results are analyzed under both mandatory and voluntary labeling. Ibanez and Grolleau (2008) consider a model where products can only be produced at two discrete levels of quality, but that even firms producing the lower quality good can obtain an eco-label. Amacher, Koskela, and Ollikainen (2004) use a model with two discrete levels of quality, but the cost to achieve quality is dependent on both a fixed and variable component. Konishi (2011) considers a model with discrete quality levels that allows entry and exit from the market. Rodriguez-Ibeas (2007) uses a model where consumers are separated between green and brown types, and green types perceive the environmentally friendly product to be of higher quality. Ben Youssef and Lahmandi-Ayed (2008) develop a model where labeled products are assumed to have the minimum quality needed to meet a standard set by a labeling authority, and the focus is on the choice of minimum quality set by the labeling standard.

In models where the label is voluntary, the issue of how consumers perceive an unlabeled product is an important issue. In Bonroy and Constantatos (2008) each consumer has a subjective probability regarding which firm they believe produces the higher quality good. Ibanez and Grolleau (2008) model consumers that know the available quality levels, but form beliefs based on the labeling choices of the firms. Labeled products are believed to be high quality with greater probability than unlabeled products, and consumers can not distinguish in quality between two products with labels. Ben Youssef and Lahmandi-Ayed (2008) assume unlabeled products to be of a fixed, minimum level of quality.

Finally, models may differ in how the certification is obtained. In most models the certification process required to use a label perfectly informs consumers about the product's quality. In some cases there may be no process to prevent low quality firms from using the eco-label (Ibanez and Grolleau, 2008). Kirchhoff (2000) allows for companies to falsely claim high environmental quality, but are subject to monitoring that can detect false claims. Mason (2011) considers a system with a fixed fee for certification, but an imperfect certification test. The price consumers are willing to pay for unlabeled products are based on rational beliefs given the probability of passing or failing the test.

Our model of a carbon label is one with a continuous label value; a voluntary, third party, fixed cost of certification that perfectly informs consumers of the product quality; and falls under the category of a Type III label. The characteristics of a voluntary, continuous label appears to be a novel approach. Roe and Sheldon (2007) consider labels that are voluntary or continuous, but do not study both in combination. We consider the impact of a carbon label in the context of an extended version of the standard two-stage game of vertical product differentiation. In the first stage the firms simultaneously decide whether or not to pursue a labeling strategy. As before, firms simultaneously choose quality in the second stage, incurring a fixed cost to achieve the chosen quality level, after observing their competitors strategy on labeling. Finally, in the third stage the companies again simultaneously choose price given the quality and labeling choices made in the first two stages. Firms choosing to label incur a fixed cost L and consumers are then perfectly informed about the level of quality of the product. The cost of the label is assumed to include the cost of both measuring the carbon footprint through an LCA as well as the cost paid to the third party to certify the results. If only one firm chooses to label its product consumers will assume the unlabeled product has a quality, s_u, that is some linear combination of the labeled product's quality and a product of quality zero. All consumers have the same perception of the unlabeled product's quality, and this perception is exogenously given by $\lambda \in [0, 1)$, such that $s_u = \lambda s_l$, where s_l is the quality of the labeled product. This mechanism is similar in some ways to the one used by Jinji (2004), but our perceived quality falls between the minimum quality and the quality of a labeled product, rather than between the actual quality and an average quality level. By studying the choices over a range of consumer perceptions we gain insight to how changes in consumer perception of the label influence outcomes.

Given this structure, there are four possible outcomes to this game, again assuming that if the firms differ in quality Firm 2 is the higher quality firm:

1. Neither firm labels.
2. Both firms label.
3. Firm 2 labels, Firm 1 does not.
4. Firm 1 labels, Firm 2 does not.

Parameter	Firm 1	Firm 2
Price (p)	$\frac{\bar{\theta}^2\mu^2(4\mu-7)(\mu-1)}{2\alpha(4\mu-1)^4}$	$\frac{8\bar{\theta}^2\mu(4\mu^2-3\mu+2)(\mu-1)}{2\alpha(4\mu-1)^4}$
Quality (s)	$\frac{\bar{\theta}\mu^2(4\mu-7)}{2\alpha(4\mu-1)^3}$	$\frac{4\bar{\theta}\mu(4\mu^2-3\mu+2)}{2\alpha(4\mu-1)^3}$
Quantity (q)	$\frac{\mu}{(4\mu-1)}$	$\frac{2\mu}{(4\mu-1)}$
Profit (Π)	$\frac{\bar{\theta}^2\mu^3(4\mu-7)(4\mu^2-3\mu+2)}{4\alpha(4\mu-1)^6} - L$	$\frac{16\bar{\theta}^2\mu^3(4\mu^2-3\mu+2)(4\mu-7)}{4\alpha(4\mu-1)^6} - L$

Table 7.2: Summary of Scenario 2

We first consider each of the cases individually, and then consider the resulting equilibriums given various parameter values.

7.4.1 Case 1—Neither Firm Labels

If neither firm labels then the products will be undifferentiated in the market. In this situation both firms will price at marginal cost. Profits for both firms will thus be decreasing in the level of quality investment, and both firms will choose a quality level of $s_1 = s_2 = 0$ and earn zero profits.

7.4.2 Case 2—Both Firms Label

When both firms choose to label consumers will be perfectly informed regarding the quality of each product. Since the choice of quality and price are independent of the fixed cost required for labeling, the outcome of the quality and price game is the same as in the basic model of vertical differentiation discussed in Section 7.3. The only difference is that now both firms incur the cost of obtaining the label, and their profits are reduced by L. The results are shown again in Table 7.2, with the reduced profits for each firm.

7.4.3 Case 3—Only the High Quality Firm Labels

When Firm 2 chooses to label and Firm 1 does not, the perceived quality of Firm 1's product in the market is independent of its choice of quality. By substituting $s_1 = \lambda s_2$ in the profit functions for each firm we get the following expressions:

$$\Pi_1(p_1, p_2, s_1, s_2) = p_1 q_1 - \alpha s_1^2 = \frac{p_1}{\bar{\theta}}\left(\frac{p_2 - p_1}{s_2 - \lambda s_2} - \frac{p_1}{\lambda s_2}\right) - \alpha s_1^2 \tag{7.23}$$

$$\Pi_2(p_1, p_2, s_1, s_2) = p_2 q_2 - \alpha s_2^2 = \frac{p_2}{\bar{\theta}}\left(\bar{\theta} - \frac{p_2 - p_1}{s_2 - \lambda s_2}\right) - \alpha s_2^2 - L \tag{7.24}$$

Differentiating each profit function with respect to the firm's price gives the following first order conditions:

$$\frac{\partial \Pi_1}{\partial p_1} = 0 \Rightarrow \frac{1}{\bar{\theta}}\left(\frac{p_2 - p_1}{s_2 - \lambda s_2} - \frac{p_1}{\lambda s_2}\right) + \frac{p_1}{\bar{\theta}}\left(-\frac{1}{s_2 - \lambda s_2} - \frac{1}{\lambda s_2}\right) = 0 \tag{7.25}$$

$$\frac{\partial \Pi_2}{\partial p_2} = 0 \Rightarrow \frac{1}{\bar{\theta}}\left(\bar{\theta} - \frac{p_2 - p_1}{s_2 - \lambda s_2}\right) + \frac{p_2}{\bar{\theta}}\left(-\frac{1}{s_2 - \lambda s_2}\right) = 0 \tag{7.26}$$

Solving for p_1 and p_2 produces:

$$p_1 = \frac{\lambda p_2}{2} \tag{7.27}$$

$$p_2 = \frac{p_1 + \bar{\theta}(s_2 - \lambda s_2)}{2} \tag{7.28}$$

Substituting one in to the other allows us to solve for p_1 and p_2 in terms of each firm's best response given the quality chosen by Firm 2:

$$p_1 = \frac{\theta s_2 \lambda (1 - \lambda)}{4 - \lambda} \tag{7.29}$$

$$p_2 = \frac{2\theta s_2 (1 - \lambda)}{4 - \lambda} \tag{7.30}$$

Rewriting the profits functions in terms of s_1 and s_2:

$$\Pi_1(s_1, s_2) = \frac{p_1}{\bar{\theta}}\left(\frac{p_2 - p_1}{s_2 - \lambda s_2} - \frac{p_1}{\lambda s_2}\right) - \alpha s_1^2 = \frac{\bar{\theta} s_2 \lambda (1 - \lambda)}{(4 - \lambda)^2} - \alpha s_1^2 \tag{7.31}$$

$$\Pi_2(s_1, s_2) = \frac{p_2}{\bar{\theta}}\left(\bar{\theta} - \frac{p_2 - p_1}{s_2 - \lambda s_2}\right) - \alpha s_2^2 - L = \frac{4\bar{\theta} s_2 (1 - \lambda)}{(4 - \lambda)^2} - \alpha s_2^2 - L \tag{7.32}$$

Parameter	Firm 1	Firm 2
Price (p)	$\frac{4\bar{\theta}^2\lambda(1-\lambda)^2}{2\alpha(4-\lambda)^3}$	$\frac{8\bar{\theta}^2(1-\lambda)^2}{2\alpha(4-\lambda)^3}$
Quality (s)	0	$\frac{4\bar{\theta}(1-\lambda)}{2\alpha(4-\lambda)^2}$
Quantity (q)	$\frac{1}{4-\lambda}$	$\frac{2}{4-\lambda}$
Profit (Π)	$\frac{4\bar{\theta}^2\lambda(1-\lambda)^2}{2\alpha(4-\lambda)^4}$	$\frac{8\bar{\theta}^2(1-\lambda)^2}{2\alpha(4-\lambda)^4} - L$

Table 7.3: Summary of Scenario 3

Maximizing profits for both firms with respect to quality choices produces the following first order conditions:

$$\frac{\partial \Pi_1}{\partial s_1} = 0 \Rightarrow -2\alpha s_1 = 0 \tag{7.33}$$

$$\frac{\partial \Pi_2}{\partial s_2} = 0 \Rightarrow \frac{4\bar{\theta}(1-\lambda)}{(4-\lambda)^2} - 2\alpha s_2 = 0 \tag{7.34}$$

Solving for s_1 and s_2, with the restriction that quality level can not be negative, we get the following result:

$$s_1 = 0 \tag{7.35}$$

$$s_2 = \frac{4\bar{\theta}(1-\lambda)}{2\alpha(4-\lambda)^2} \tag{7.36}$$

With the choices of quality now known we can determine the price, quality, quantity sold, and profit for each firm. The results are shown in Table 7.3 As we can see from Table 7.3, the choices of price, the quality level chosen by Firm 2, the quantity sold be each firm, and the profits for each firm are dependent on λ. Examining the behavior of each of these quantities with respect to λ allows us to understand the role of the consumer perception of the label. First, we look at the role of λ on the profits of the two firms as shown in Figure 7-1.

From Figure 7-1 we can see that Firm 2's profit is maximized at $\lambda = 0$, where it acts as a monopolist and sets quality and price without regard to competition from Firm 1. As λ increases, the profit for Firm 2 decreases, finally reaching a point where Firm 2 is no longer able to make a profit. We denote the value of λ where profit is zero by λ_0, and it can be obtained by setting the profit of Firm 2 to zero and solving for λ. For any value λ of such that $\lambda > \lambda_0$, Firm 2 will choose not to label as it can not make a profit doing so, and thus price, quality, and profits for both Firm 1 and Firm 2 will be zero. Firm 1 earns zero profit

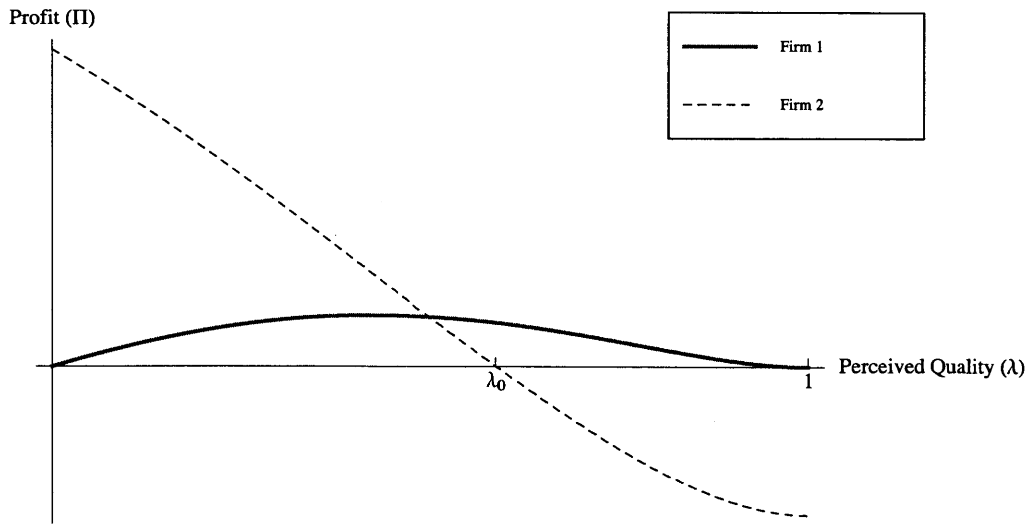


Figure 7-1: Total Profits

when $\lambda = 0$, as the product is correctly perceived as a zero quality product by consumers at this point. As λ increases, consumers begin to perceive Firm 1's product has having a positive level of quality, allowing Firm 1 to charge a small price premium and earn a positive profit. At some point profits begin to decline for Firm 1, as higher values of λ result in a decline in the quality chosen by Firm 2 and less opportunity for Firm 1 to capture value at the low end of the market. The decline in the level of quality chosen by Firm 2 is shown in Figure 7-2.

The quality choice of Firm 2 is decreasing in λ over the range of $\lambda \in [0, 1]$. However, Firm 2 cannot earn a profit by labeling for any value above λ_0, and will thus choose a quality level of zero and no label beyond that point. As λ increases the value obtained by Firm 2 for an increase in quality is reduced due to Firm 1 also being credited by consumers for some perceived quality increase. Due to the increasing marginal cost of quality improvements the effect is to reduce the optimal level of quality chosen by Firm 2.

Figure 7-3 shows the prices chosen by Firm 1 and Firm 2 across the values of λ. At $\lambda = 0$ Firm 2 acts as a monopolist and faces no competition from Firm 1. As λ increases Firm 1 is able to charge a slight premium due to it's perceived quality. Facing this competition, Firm

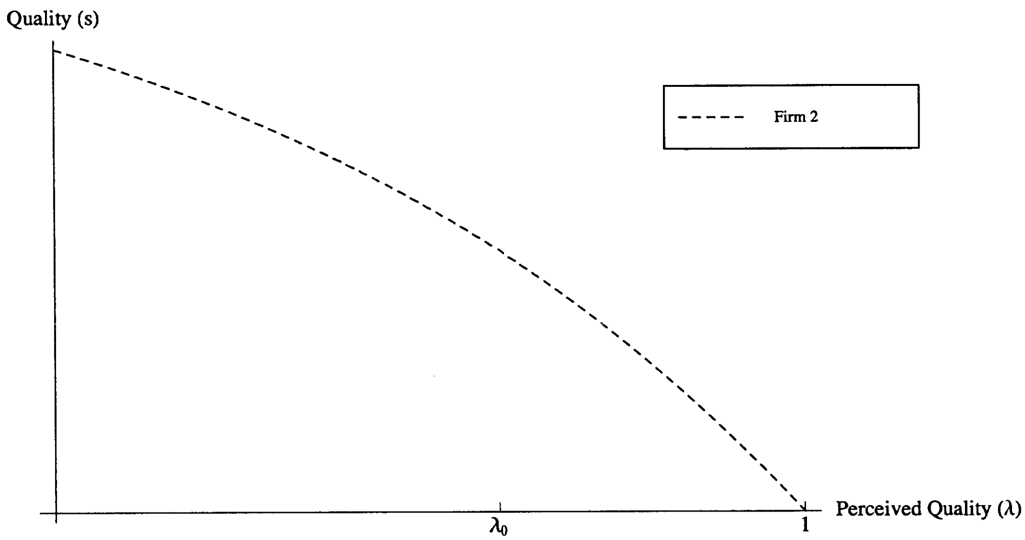


Figure 7-2: Quality Level

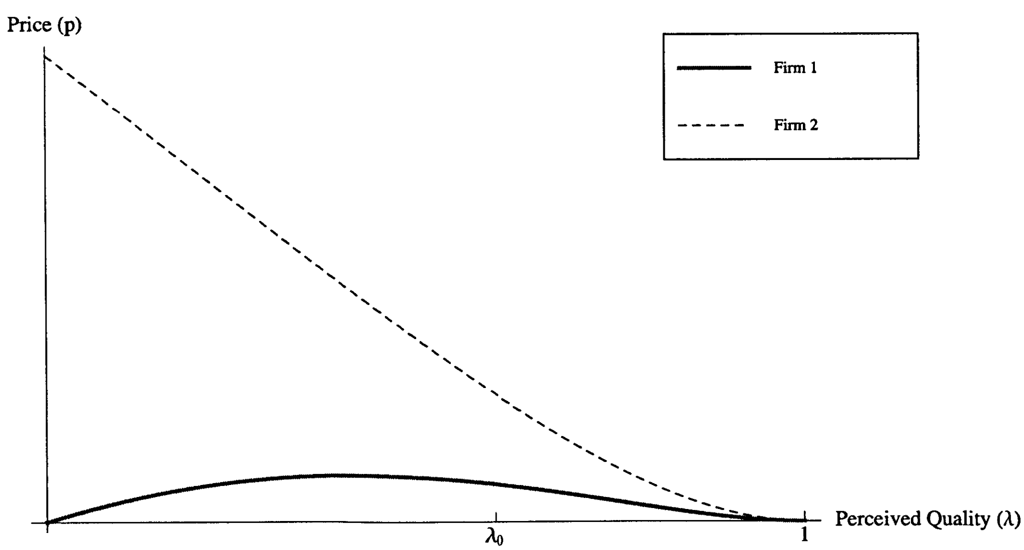


Figure 7-3: Prices

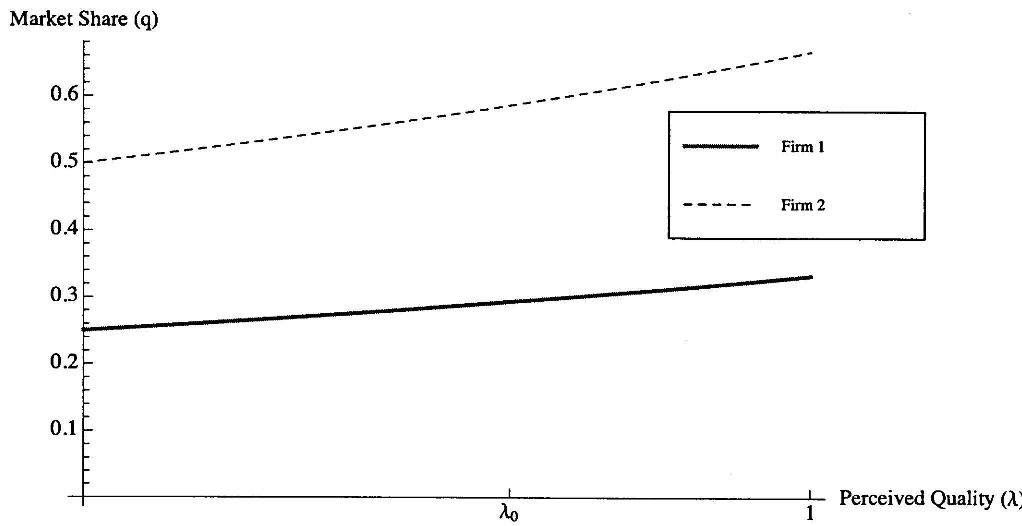


Figure 7-4: Quantity Sold

2 reduces quality, and must then reduce price in order to maintain market share.

In Figure 7-4 we see the quantities sold by each firm. At $\lambda = 0$ Firm 2 sells to exactly half the market while acting as a monopolist. The remaining half of the market is indifferent between Firm 1's product and no product at all. As λ increases, Firm 1's sales increase from a quarter of the market, while Firm 2's sales increase to always be double that of Firm 1. The increased sales for Firm 1 are driven by its perceived quality being greater than 0, and increasing as λ increases. Firm 2's sales are driven by its lowering of price in response to competition from Firm 1, offsetting a drop in quality level from that chosen in the monopolist scenario.

7.4.4 Case 4—Only the Low Quality Firm Labels

There is no situation where Firm 2 would choose higher quality than Firm 1 in a market where Firm 1 labels and Firm 2 does not. If Firm 2 chooses not to label then its sales quantity and price are independent of its choice of quality level. In this case choosing a quality level of zero and incurring no fixed costs for quality improvements maximizes its profit. For Firm 1 to earn a positive profit it must choose a quality level and price greater than zero, but this contradicts the assumption that $s_2 > s_1$. If Firm 1 chooses a quality level equal to zero it must also choose a price of zero in order to compete with Firm 2, and earn a total profit of $-L$. Thus, either Firm 1 is the high quality firm, and should be designated Firm 2 with analysis proceeding from Case 3, or it earns a negative profit and would be better off not labeling its product.

7.4.5 Equilibrium Conditions

We begin with the conditions under which Firm 1 will never choose to label. Examining the profit functions for the case when both firms label we can see that Firm 1 earns the lower profit, and there exists some value of L at which this profit is zero. Substituting the numeric value of $\mu = 5.2512$ and simplifying the expression gives that value as:

$$L = .00076\frac{\bar{\theta}^2}{\alpha} \tag{7.37}$$

When L is greater than this value Firm 1 will never choose to label, as it cannot earn a positive profit when Firm 2 also chooses to label.

With this restriction in place we can now examine the conditions where Firm 2 chooses to label given that Firm 1 will not. From Firm 2's profit function shown in Table 7.3 we can see that Firm 2's profits are decreasing in λ, and thus maximized at $\lambda = 0$. When $\lambda = 0$ Firm 2 acts as a monopolist and earns the following profit:

$$\Pi_2 = \frac{\bar{\theta}^2}{64\alpha} - L \tag{7.38}$$

For Firm 2 to earn a positive profit, we must have $L < \frac{\bar{\theta}^2}{64\alpha}$, otherwise Firm 2 will choose not to label regardless of the value of λ. For any value of L, $.00076\frac{\bar{\theta}^2}{\alpha} < L < \frac{\bar{\theta}^2}{64\alpha}$, there exists a critical value of λ, designated λ_0, for which Firm 2 earns zero profit when it chooses to label. If $\lambda < \lambda_0$ then profits are positive with labeling and Firm 2 will invest in the label. For values of $\lambda > \lambda_0$ profits would be negative with a label, and so neither firm invests in a label.

Examples of Firm 2's profit as a function of λ are shown in Figure 7-5 with both high and

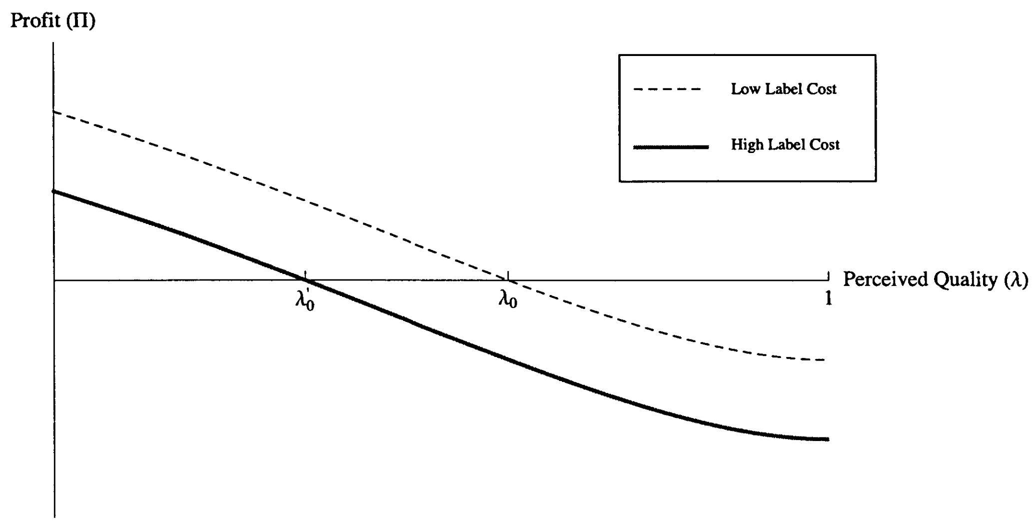


Figure 7-5: Firm 2 Profits

low label costs. Increasing the cost of the label shifts the profit function for Firm 2 down. With higher labeling costs the value of λ where labeling is no longer profitable, shown by λ_0', is less than in the case with a low labeling cost, shown by λ_0. Thus, an increase in the cost of the label limits the range of values of λ for which labeling is profitable.

When $L < .00076\frac{\bar{\theta}^2}{\alpha}$ both Firm 1 and Firm 2 are able to earn a profit by labeling. However, for certain values of λ and L, Firm 1 is able to earn a higher profit by not labeling. Figure 7-6 shows the profit for Firm 1 under both labeling decisions as a function of λ. Since profits are independent of λ in the case where both firms label the profit for Firm 1 is constant across all values of λ. When Firm 1 chooses not to label, profits are zero when $\lambda = 0$ and increase to a maximum value before declining to zero again when $\lambda = 1$.

Intuitively, at $\lambda = 0$ the product is perceived by customers as a zero quality product and they are unwilling to pay a premium, and $p = 0$. As λ increases the perceived quality of the product increases, and Firm 1's profit increases as it raises price and sells a higher quantity. This continues until λ reaches a critical value where profits are maximized for Firm 1. As λ increases beyond this value the perceived quality of Firm 1's product is too close to that of Firm 2 and the firms engage in price competition, which lowers the selling price for Firm 1

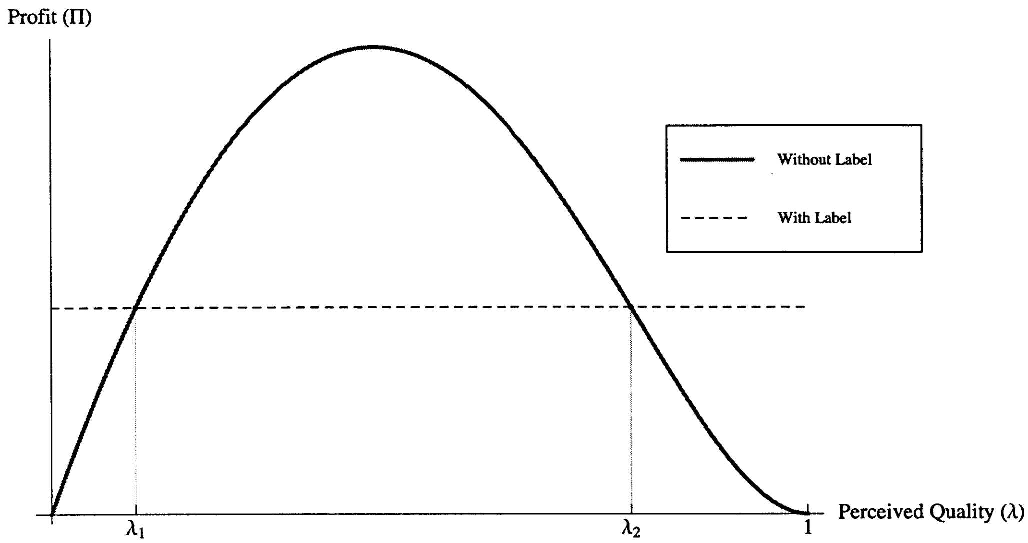


Figure 7-6: Firm 1 Profits

and reduces profits. At $\lambda = 1$ the products are perceived as identical in quality and the firms engage in straight price competition, driving the selling price and profits to zero. As seen from Figure 7-6 there will be exactly two values of λ between zero and one for which profits for Firm 1 are equivalent whether it labels or not. These values can be found by solving the following equality for λ :

$$\frac{2\bar{\theta}^2\lambda(1-\lambda)^2}{\alpha(4-\lambda)^4} = \frac{\bar{\theta}^2\mu^3(4\mu-7)(4\mu^2-3\mu+2)}{4\alpha(4\mu-1)^6} - L \tag{7.39}$$

Let λ_1 and λ_2 be the solutions to this equation, with $\lambda_1 < \lambda_2$. Important to the consideration of Firm 1's decision to label is the fact that an increase in the cost of labeling does not affect the profits of the firm when it chooses not to label, but reduces profit if it does label. In Figure 7-7 we can see the impact of the increase in labeling cost. The profits from the labeling case are shifted down, while the profits from the non-labeling case remain the same. This results in a shift in the values of λ_1 and λ_2 to new points, shown by $\lambda_1^{'}$ and $\lambda_2^{'}$. This shift decreases the range of values of λ for which Firm 1 would choose to label.

Given these definitions we are now ready to characterize the full range of pure strategy

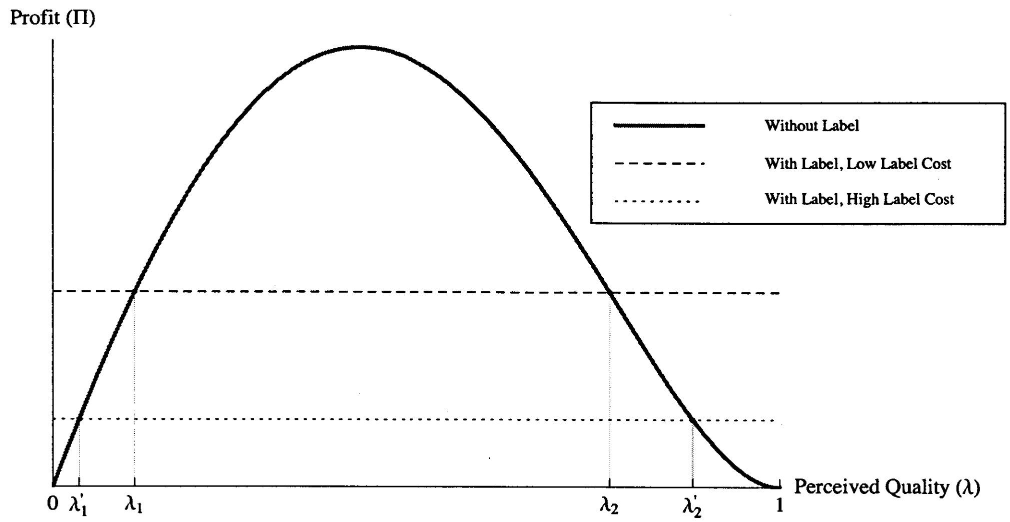


Figure 7-7: Firm 1 Profits Under High and Low Labeling Costs

equilibria for Firm 1 and Firm 2 given the possible values of L, $\bar{\theta}$, α, and λ. These results are summarized in Table 7.4. From these results we can see that there are two key factors regarding the label that drive the labeling decision: the relative cost of the label and the consumer perception of unlabeled products. When the label is relatively cheap both firms are able to earn a profit by investing in a label, but the lower quality firm only wants to invest in a label if consumer perception of unlabeled products is either very high or very low. As the cost of providing a label increases, it is no longer possible for the low quality firm to earn a profit by labeling. The high quality firm will be the only one to label, and then only when consumer perception of unlabeled products is sufficiently low to allow the high quality firm to differentiate its product in a cost effective manner. Finally, as the cost of the label grows too high no firm will be able to earn a profit with labeling, and both firms will sell an undifferentiated product of zero quality.

These three distinct regions can be seen in Figure 7-8. The light shaded regions shows the values of L and λ for which only Firm 2 labels, while the darker shaded regions shows the values for which both firms label. Above the critical value of $\frac{\bar{\theta}^2}{64\alpha}$ neither firm will choose to label. As L decreases from this critical value the range of scenarios where firms choose

Label Cost (L)	Perceived Quality (λ)	Firm 1 Decision	Firm 1 Profit	Firm 2 Decision	Firm 2 Profit
$0 < L < .00076\frac{\bar{\theta}^2}{\alpha}$	$\lambda < \lambda_1$ or $\lambda > \lambda_2$	Label	$\frac{\bar{\theta}^2\mu^3(4\mu-7)(4\mu^2-3\mu+2)}{4\alpha(4\mu-1)^6} - L$	Label	$\frac{16\bar{\theta}^2\mu^3(4\mu^2-3\mu+2)(4\mu-7)}{4\alpha(4\mu-1)^6} - L$
$0 < L < .00076\frac{\bar{\theta}^2}{\alpha}$	$\lambda_1 < \lambda < \lambda_2$	No Label	$\frac{2\bar{\theta}^2\lambda(1-\lambda)^2}{\alpha(4-\lambda)^4}$	Label	$\frac{4\bar{\theta}^2(1-\lambda)^2}{\alpha(4-\lambda)^4} - L$
$.00076\frac{\bar{\theta}^2}{\alpha} < L < \frac{\bar{\theta}^2}{64\alpha}$	$\lambda < \lambda_0$	No Label	$\frac{2\bar{\theta}^2\lambda(1-\lambda)^2}{\alpha(4-\lambda)^4}$	Label	$\frac{4\bar{\theta}^2(1-\lambda)^2}{\alpha(4-\lambda)^4} - L$
$.00076\frac{\theta^2}{\alpha} < L < \frac{\theta^2}{64\alpha}$	$\lambda > \lambda_0$	No Label	0	No Label	0
$L > \frac{\theta^2}{64\alpha}$	any	No Label	0	No Label	0

Table 7.4: Equilibrium Results

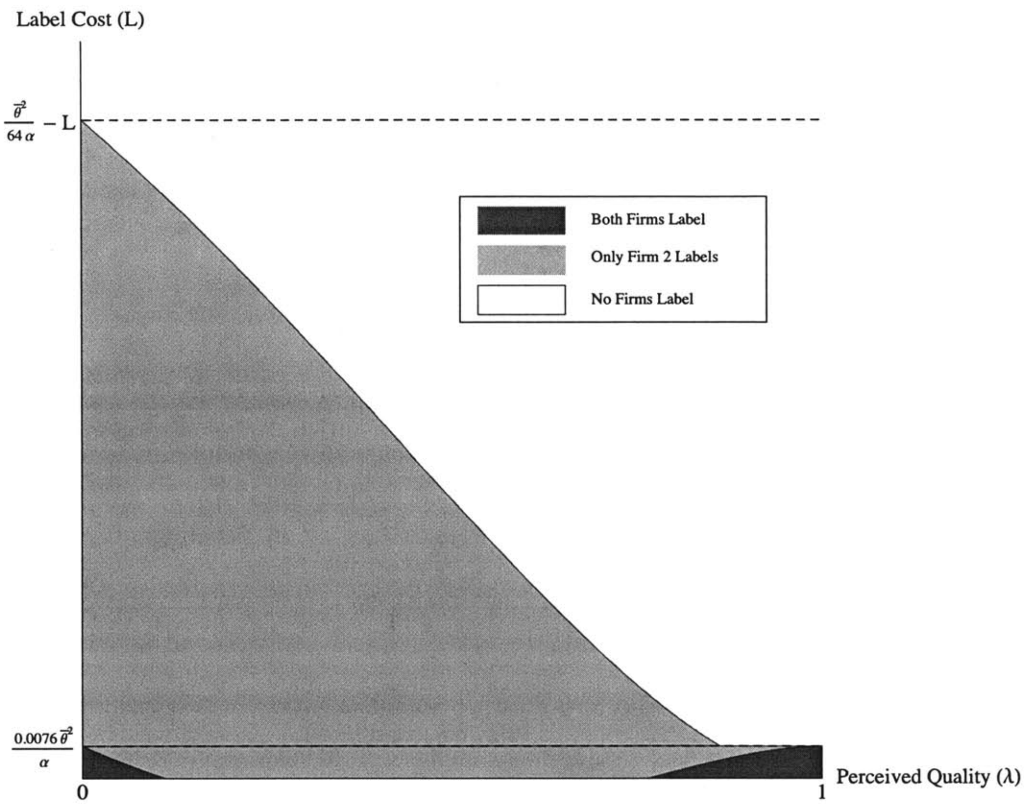


Figure 7-8: Equilibrium Labeling Choices

to label increases. For certain values of λ Firm 2 will never choose to label regardless of the cost of the label, but that range shrinks as the labeling cost is reduced. This is important when viewing the label as a means of reducing emissions. Each firm sells a quantity, q, of product, and each product's carbon footprint has been reduced by s units of emissions. The total emissions reduced, E, is thus equal to the quantity sold by each firm multiplied by the firm's quality level.

Under Scenario 2, where both firms label, the total emissions reduction is given by:

$$E = q_1 s_1 + q_2 s_2 \tag{7.40a}$$

$$= \frac{\mu}{(4\mu-1)} \frac{\overline{\theta}\mu^2(4\mu-7)}{2\alpha(4\mu-1)^3} + \frac{2\mu}{(4\mu-1)} \frac{4\overline{\theta}\mu(4\mu^2-3\mu+2)}{2\alpha(4\mu-1)^3} \tag{7.40b}$$

$$= \frac{\overline{\theta}\mu^2(36\mu^2-31\mu+16)}{2\alpha(4\mu-1)^4} \tag{7.40c}$$

$$\cong .07282\frac{\overline{\theta}}{\alpha} \tag{7.40d}$$

Under Scenario 3, where only Firm 2 labels and Firm 1 contributes no emissions reduction, the total emissions reduction is:

$$E = q_1 s_1 + q_2 s_2 \tag{7.41a}$$

$$= \frac{1}{4-\lambda} \times 0 + \frac{2}{4-\lambda} \times \frac{2\overline{\theta}(1-\lambda)}{\alpha(4-\lambda)^2} \tag{7.41b}$$

$$= \frac{4\overline{\theta}(1-\lambda)}{\alpha(4-\lambda)^3} \tag{7.41c}$$

Figure 7-9 shows the total emissions reduced, as measured by (7.40a) and (7.41a). When both firms choose to label the total emissions reduced are constant regardless of λ, as the perceived quality of unlabeled products is irrelevant when both products are labeled. When only Firm 2 chooses to label total emissions reduced are decreasing in λ.

Proposition 7.1. *Total emissions reduced are always greater in the scenario where both firms label than when only the high quality firm labels.*

Proof. Total emissions are declining in λ over the range of possible values, and are thus

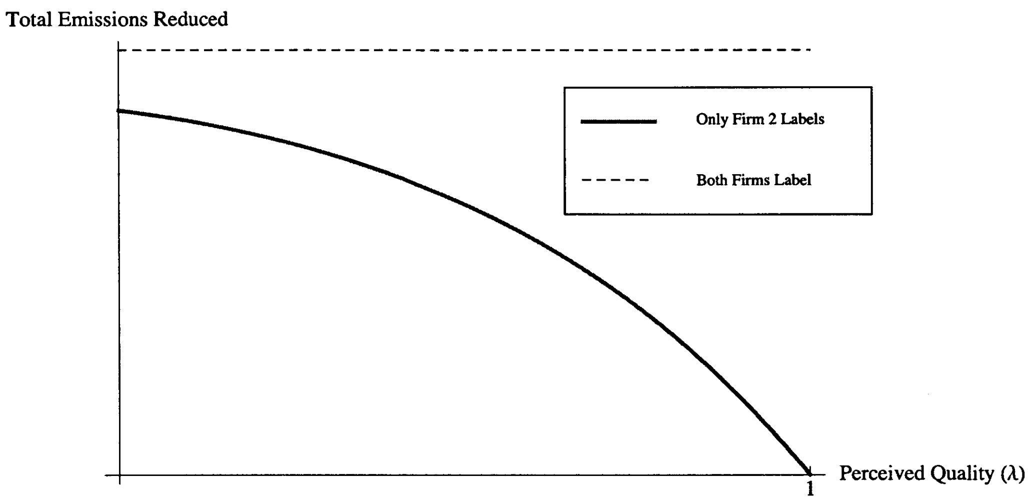


Figure 7-9: Total Emissions Reduced

maximized at $\lambda = 0$. Since $.07282\frac{\bar{\theta}}{\alpha} > \frac{4(1-0)}{(4-0)^3}\frac{\bar{\theta}}{\alpha}$ the total emissions reduced are always greater in the scenario where both firms label than when only Firm 2 does, regardless of the value of λ. □

Thus, reducing the cost of the labeling process can help reduce total carbon emissions, since the range of scenarios where both firms label increases as the cost of labeling is reduced.

Finally, we consider the total social welfare impact of the label, as measured by the sum of the consumer surplus, producer surplus, and societal benefit of the emissions reduction. Because an individual consumer can not affect the overall emissions reduction the benefits are not considered in their personal decision choice, but the overall public benefit from the emissions reduction is important in the contest of total social welfare. This is similar to the measures of social welfare used by Amacher et al. (2004) and Moraga-Gonzalez and Padron-Fumero (2002). The consumer surplus is given by the difference between what consumers would be willing to pay for the product and what they did pay. Under scenario 2 the consumer surplus for consumers that purchase from Firm 1 is given by:

$$CS_1 = q_1\left(\frac{\theta_{01}+\theta_{12}}{2}s_1 - p_1\right) \tag{7.42a}$$

$$= \frac{\bar{\theta}\mu^2(4\mu-7)}{2\alpha(4\mu-1)^3} \times \left(\frac{\frac{\bar{\theta}(\mu-1)}{(4\mu-1)} + \frac{\bar{\theta}(\mu-1)(28\mu^2-17\mu+16)}{(4\mu-1)(12\mu^2-5\mu+8)}}{2} \times \frac{\bar{\theta}\mu^2(4\mu-7)}{2\alpha(4\mu-1)^3} - \frac{\bar{\theta}^2\mu^2(4\mu-7)(\mu-1)}{2\alpha(4\mu-1)^4} \right) \tag{7.42b}$$

$$= \frac{\bar{\theta}\mu^3(\mu-1)(4\mu-7)(4\mu^2-3\mu+2)}{\alpha(4\mu-1)^5(12\mu^2-5\mu+8)} \tag{7.42c}$$

$$\cong .00083\frac{\bar{\theta}^2}{\alpha} \tag{7.42d}$$

And that of the consumers that purchase from Firm 2 is:

$$CS_2 = q_2\left(\frac{\theta_{12}+\bar{\theta}}{2}s_2 - p_2\right) \tag{7.43a}$$

$$= \frac{2\mu}{(4\mu-1)} \left(\frac{\frac{\bar{\theta}(\mu-1)(28\mu^2-17\mu+16)}{(4\mu-1)(12\mu^2-5\mu+8)} + \bar{\theta}}{2} \times \frac{4\bar{\theta}\mu(4\mu^2-3u+2)}{2\alpha(4\mu-1)^3} - \frac{8\bar{\theta}^2\mu(4\mu^2-3u+2)(\mu-1)}{2\alpha(4\mu-1)^4} \right) \tag{7.43b}$$

$$= \frac{2\bar{\theta}^2\mu^2(4\mu^2-3\mu+2)(28\mu^3-9\mu^2+18\mu+8)}{\alpha(4\mu-1)^5(12\mu^2-5\mu+8)} \tag{7.43c}$$

$$\cong .02078\frac{\bar{\theta}^2}{\alpha} \tag{7.43d}$$

The producer surplus is simply the total profit for each firm. If we define a non-negative value, ρ, to be the societal benefit in dollars per unit of emissions reduction then the total social welfare when both firms label is:

$$SW = CS_1 + CS_2 + \Pi_1 + \Pi_2 + \rho E \tag{7.44a}$$

$$\cong .00083\frac{\bar{\theta}^2}{\alpha} + .02078\frac{\bar{\theta}^2}{\alpha} + .00076\frac{\bar{\theta}^2}{\alpha} - L + .01222\frac{\bar{\theta}^2}{\alpha} - L + .07282\frac{\rho\bar{\theta}}{\alpha} \tag{7.44b}$$

$$\cong \frac{\bar{\theta}}{\alpha}\left(.03459\bar{\theta} + .07282\rho\right) - 2L \tag{7.44c}$$

Applying the same approach to Scenario 3 where only Firm 2 labels we can define the consumer surplus for consumers that buy from Firm 1 as:

$$
\begin{aligned}
CS_1 =& q_1\left(\frac{\theta_{01}+\theta_{12}}{2}\lambda s_2 - p_1\right) && (7.45a)\\
=& \frac{1}{4-\lambda}\left(\frac{\frac{\bar{\theta}(1-\lambda)}{4-\lambda}+\frac{\bar{\theta}(2-\lambda)}{4-\lambda}}{2}\times\frac{2\lambda\bar{\theta}\,(1-\lambda)}{\alpha\,(4-\lambda)^2}-\frac{2\bar{\theta}^2\lambda(1-\lambda)^2}{\alpha(4-\lambda)^3}\right) && (7.45b)\\
=& \frac{\bar{\theta}^2\lambda\,(1-\lambda)}{\alpha(4-\lambda)^4} && (7.45c)
\end{aligned}
$$

And those that buy from Firm 2 as:

$$
\begin{aligned}
CS_2 =& q_2\left(\frac{\hat{\theta}_{12}+\hat{\bar{\theta}}}{2}s_2 - p_2\right) && (7.46a)\\
=& \frac{2}{4-\lambda}\left(\frac{\frac{\bar{\theta}(2-\lambda)}{4-\lambda}+\bar{\theta}}{2}\times\frac{2\bar{\theta}(1-\lambda)}{\alpha(4-\lambda)^2}-\frac{4\bar{\theta}^2(1-\lambda)^2}{\alpha(4-\lambda)^3}\right) && (7.46b)\\
=& \frac{4\bar{\theta}^2(1-\lambda^2)}{\alpha(4-\lambda)^4} && (7.46c)
\end{aligned}
$$

Of note is that the consumer surplus for those who buy from Firm 1 is based on the perceived quality of the product, not the actual quality. This is because the utility of the consumer is based on the feeling of having done something good, and thus the consumer surplus is measured based on the consumer's perception of the quality of the product.

Combining the consumer surplus with the firm profit functions gives the following expression for social welfare:

$$
\begin{aligned}
SW =& CS_1 + CS_2 + \Pi_1 + \Pi_2 + \rho E && (7.47a)\\
=& \frac{\bar{\theta}^2\lambda\,(1-\lambda)}{\alpha(4-\lambda)^4}+\frac{4\bar{\theta}^2(1-\lambda^2)}{\alpha(4-\lambda)^4}+\frac{2\bar{\theta}^2\lambda(1-\lambda)^2}{\alpha(4-\lambda)^4}+\frac{8\bar{\theta}^2(1-\lambda)^2}{2\alpha(4-\lambda)^4}-L+\rho\frac{4\bar{\theta}(1-\lambda)}{\alpha(4-\lambda)^3} && (7.47b)\\
=& \frac{\bar{\theta}^2\,(2\lambda^3-5\lambda^2-5\lambda+8)+4\rho\bar{\theta}\,(\lambda^2-5\lambda+4)}{\alpha\,(4-\lambda)^4}-L && (7.47c)
\end{aligned}
$$

Figure 7-10 shows the social welfare under these two labeling results. From this we can see that ignoring any costs of labeling the total social welfare is greater under the scenario where both firms label for all values of λ. The cost of the label acts on a drag on the total social welfare, as the costs incurred by the firms to obtain the label reduce profits without

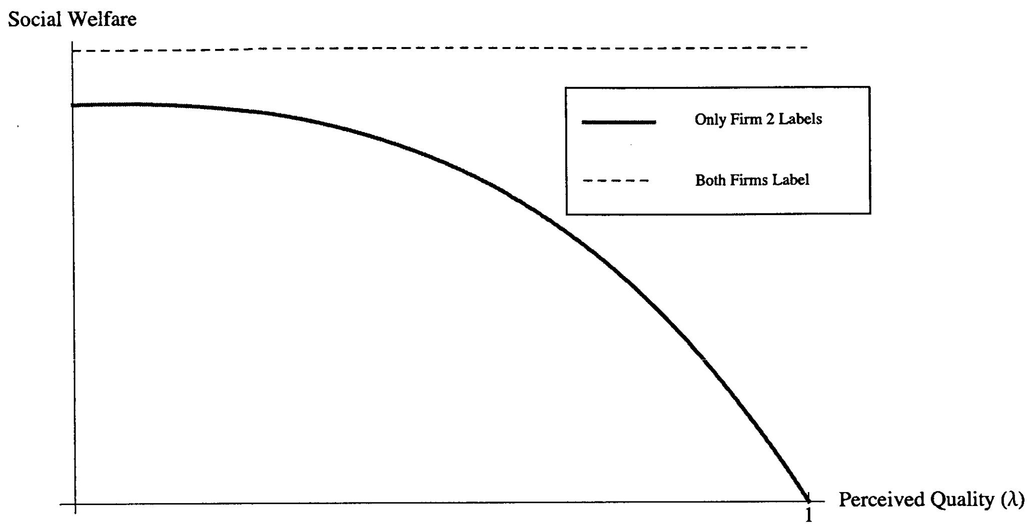


Figure 7-10: Social Welfare

increasing the consumer surplus or the amount of emissions reduced. When we consider the cost of the label the total social welfare is higher when both firms label provided the following inequality is true:

$$\frac{\bar{\theta}}{\alpha}\left(.03459\bar{\theta} + .07282\rho\right) - 2L > \frac{\bar{\theta}^2\left(2\lambda^3 - 5\lambda^2 - 5\lambda + 8\right) + 4\rho\bar{\theta}\left(\lambda^2 - 5\lambda + 4\right)}{\alpha\left(4-\lambda\right)^4} - L \qquad (7.48)$$

Proposition 7.2. *Under the scenario where both firms choose to label total social welfare will be greater than when only the high quality firm labels.*

Proof. Solving (7.48) for L give the total social welfare as being greater when both firms label provided:

$$L < \frac{\bar{\theta}^2}{\alpha}\left(.03459 - \frac{2\lambda^3 - 5\lambda^2 - 5\lambda + 8}{\left(4-\lambda\right)^4}\right) + \frac{\bar{\theta}\rho}{\alpha}\left(.07282 - \frac{4\lambda^2 - 20\lambda + 16}{\left(4-\lambda\right)^4}\right) \qquad (7.49)$$

The expression on the right hand side reaches a minimum of $.00334\frac{\bar{\theta}^2}{\alpha} + .01032\frac{\bar{\theta}\rho}{\alpha}$ at $\lambda = 0$. Recall that our criteria for both firms labeling requires $L < .00076\frac{\bar{\theta}^2}{\alpha}$. Thus, under any scenario where both firms choose to label, the social welfare will always be greater than when only the high quality firm labels, regardless of the value of λ. □

Proposition 7.3. *Reducing the cost of the label increases total social welfare.*

Proof. Under any outcome of the labeling game the consumer surplus and societal benefit are independent of the cost of the label, while the producer surplus is decreasing. Thus, with no change in the labeling decision, social welfare will increase as the cost of the label decreases. Further, a decrease in the cost of the label can only induce more firms to label, and at a given value of λ an increase in the number of firms labeling results in an increase in social welfare. If neither firm chooses to label, even at a lower cost of the label, then total social welfare is unchanged. Thus, social welfare is either increased or unchanged by lowering the cost of the label. □

7.4.6 Discussion

An analysis of the social welfare shows that the scenario where both firms choose to label produces the most benefit. This suggests that the authority that administers the label should focus on reducing the cost required to obtain the label in order to encourage more labeling. In most cases social welfare can also be improved by informing consumers regarding the benefits of labeled products, and thus reducing the perceived quality of unlabeled products. However, in one specific situation this may have a negative result. Referring to Figure 7-8, a reduction in λ is associated with a shift to the left on the figure. If both firms currently label, and the value of λ is greater than λ_2, a shift to the left could induce Firm 1 to stop labeling, which would result in a decrease in social welfare. In all other cases the decrease in λ would result in higher social welfare, either by inducing more labeling or by increasing social welfare in the situation where only Firm 2 labels.

The issues we identify as key to the success of the label are supported by the real world experience of initial carbon labeling programs. Despite the initial strong support offered by Tesco the company recently announced a decision to suspend its carbon labeling program, citing the failure of other retailers to follow suit in adding labels and the months of work required to calculate the carbon footprint of a product (Vaughan, 2012). Several other large companies have estimated the cost of measuring the carbon footprint for a single SKU at

£25,000 to £30,000 (McKinnon, 2010). While the costs of obtaining an eco-label are often substantial (Ibanez and Grolleau, 2008) this seems to be particularly true for carbon labels, where the measurement required to get the label is complex and costly (Brenton, Edwards-Jones, and Jensen, 2009).

In addition to the high cost of measuring and obtaining the label, a number of sources have cited consumer understanding as a key issue. Crespi and Marette (2003) identify the consumer's ability to understand the label to be a key point regarding the success of any label. After the introduction of the carbon label a number of questions were raised regarding its effectiveness in communicating to consumers (Boardman, 2008). Others have questioned whether the accuracy of current measurement programs is high enough to support comparing alternative products (de Koning, Schowanek, Dewaele, Weisbrod, and Guinée, 2010). Gadema and Oglethorpe (2011) found consumers to have a high preference motivation for carbon labelled products, but many were confused by the the labels. Upham, Dendler, and Bleda (2010) found that simply providing the emissions value for a product was not enough to significantly influence product selection. If consumer understanding and acceptance of labels does not improve, changes to the information on the label may be necessary. Some proposals call for better metrics than simply communicating the carbon footprint of the product (Zhao, Deutz, Neighbour, and McGuire, 2012). Experiments with color coded carbon labels that correspond to below average, near average, and above average levels of carbon emissions have shown high interest from consumers and media, but the increase in sales for the lower carbon product failed to reach statistical significance (Vanclay et al., 2011). In the next section we explore the possible change by considering the use of the more common Type I certification eco-label. Under this style of label the labeling authority defines some standard of quality, and firms that meet this standard are awarded the right to use the label on their product. Thus, rather than communicating an actual value of a specific attribute, the label instead certifies that the company has met the quality requirements of the label. We refer to this type of label as a discrete label, because the labeling communicates a binary attribute–the product either is or is not certified. We distinguish this from our standard carbon label model, which we refer to as a continuous label, since it communicates an exact level of quality that can take on a continuous range of values.

7.5 Discrete Label

We again consider the case of two firms operating in a duopoly with the same parameters as before regarding consumer types and the cost of carbon reduction. Rather than a continuous labeling mechanism we instead consider a discrete label. To achieve the label a firm must meet a minimum quality threshold of s_{min}. A firm that meets this threshold may again pay L to have the quality certified by a third party and earn the right to use the certification label on their product. Any product with a label will be perceived by consumers to have a quality of s_h. Any product without a label is assumed to be of quality s_l.

Unlike our previous labeling model only one firm will possibly choose to label under this scheme. If both firms were to label their products, they would be perceived to be of identical quality, and price would fall to marginal cost (again assumed to be zero) resulting in a loss of L for both firms. We designate the firm that chooses to label as Firm 2 and find the consumer indifferent between the two products by setting the utility of purchasing from Firm 1 and Firm 2 equal:

$$\hat{\theta}_{12}s_h - p_2 = \hat{\theta}_{12}s_l - p_1 \tag{7.50}$$

Solving 7.50 for $\hat{\theta}_{12}$ gives the consumer indifferent between the products as the one where:

$$\hat{\theta}_{12} = \frac{p_2 - p_1}{s_h - s_l} \tag{7.51}$$

The consumer indifferent between the low quality product and no product at all is noted by $\hat{\theta}_{01}$ and is determined by setting the utility of purchasing the low quality product equal to 0.

$$\hat{\theta}_{01}s_l - p_1 = 0 \tag{7.52}$$

Solving 7.52 for $\hat{\theta}_{01}$ gives the indifferent consumer as the one where:

$$\hat{\theta}_{01} = \frac{p_1}{s_l} \tag{7.53}$$

With these consumers identified we can determine the market share for each of the firms. All consumers with $\theta > \hat{\theta}_{12}$ choose the higher quality product, while those with $\hat{\theta}_{01} < \theta < \hat{\theta}_{12}$ choose the lower quality product. Consumers with $\theta < \hat{\theta}_{01}$ choose no product at all. Normalizing the total size of the market to 1 the quantities sold by each firm, q_1 and q_2, are given by:

$$q_1 = \frac{\hat{\theta}_{12} - \hat{\theta}_{01}}{\bar{\theta}} = \frac{1}{\bar{\theta}}\left(\frac{p_2 - p_1}{s_h - s_l} - \frac{p_1}{s_l}\right) \tag{7.54}$$

$$q_2 = \frac{\bar{\theta} - \hat{\theta}_{12}}{\bar{\theta}} = \frac{1}{\bar{\theta}}\left(\bar{\theta} - \frac{p_2 - p_1}{s_h - s_l}\right) \tag{7.55}$$

With these prices and qualities we can write the profit function for each firm as follows:

$$\Pi_1\left(p_1, p_2, s_1, s_2\right) = p_1 q_1 - \alpha s_1^2 = \frac{p_1}{\bar{\theta}}\left(\frac{p_2 - p_1}{s_h - s_l} - \frac{p_1}{s_l}\right) - \alpha s_1^2 \tag{7.56}$$

$$\Pi_2\left(p_1, p_2, s_1, s_2\right) = p_2 q_2 - \alpha s_2^2 = \frac{p_2}{\bar{\theta}}\left(\bar{\theta} - \frac{p_2 - p_1}{s_h - s_l}\right) - \alpha s_2^2 - L \tag{7.57}$$

We begin by solving the second stage of the game and note that the prices are independent of the actual quality choices of the firms, based instead on the consumer perceptions of labeled and unlabeled products. To do this we maximize each firm's profit function with respect to its price, producing the following first order conditions:

$$\frac{\partial \Pi_1}{\partial p_1} = 0 \Rightarrow \frac{1}{\bar{\theta}}\left(\frac{p_2 - p_1}{s_h - s_l} - \frac{p_1}{s_l}\right) - \frac{p_1}{\bar{\theta}}\left(\frac{1}{s_h - s_l} + \frac{1}{s_l}\right) = 0 \tag{7.58}$$

$$\frac{\partial \Pi_2}{\partial p_2} = 0 \Rightarrow \frac{1}{\bar{\theta}}\left(\bar{\theta} - \frac{p_2 - p_1}{s_h - s_l}\right) - \frac{p_2}{\bar{\theta}}\left(\frac{1}{s_h - s_l}\right) = 0 \tag{7.59}$$

Solving the first order conditions produces the following optimal prices in response to the other firm's price and the perceived quality of their product:

$$p_1 = \frac{s_l p_2}{2 s_h} \tag{7.60}$$

$$p_2 = \frac{p_1 + \bar{\theta}\left(s_h - s_l\right)}{2} \tag{7.61}$$

To find each firm's best response function purely in terms of the perceived qualities we substitute 7.61 in to 7.60 and solve for p_1. This produces the following best response prices

Parameter	Firm 1	Firm 2
Price (p)	$\frac{\bar{\theta} s_l (s_h - s_l)}{4s_h - s_l}$	$\frac{2\bar{\theta} s_h (s_h - s_l)}{4s_h - s_l}$
Quality (s)	0	s_{min}
Quantity (q)	$\frac{s_h}{4s_h - s_l}$	$\frac{2s_h}{4s_h - s_l}$
Profit (Π)	$\frac{\bar{\theta} s_l s_h (s_h - s_l)}{(4s_h - s_l)^2}$	$\frac{4\bar{\theta} s_h^2 (s_h - s_l)}{(4s_h - s_l)^2} - \alpha s_{min}^2 - L$

Table 7.5: Summary of Discrete Labeling Results

for both firms:

$$p_1 = \frac{\bar{\theta} s_l (s_h - s_l)}{4s_h - s_l} \tag{7.62}$$

$$p_2 = \frac{2\bar{\theta} s_h (s_h - s_l)}{4s_h - s_l} \tag{7.63}$$

Using these prices we can now write each firm's profit as a function of the quality choices:

$$\Pi_1 (s_1, s_2) = \frac{\bar{\theta} s_l s_h (s_h - s_l)}{(4s_h - s_l)^2} - \alpha s_1^2 \tag{7.64}$$

$$\Pi_2 (s_1, s_2) = \frac{4\bar{\theta} s_h^2 (s_h - s_l)}{(4s_h - s_l)^2} - \alpha s_2^2 - L \tag{7.65}$$

From the profit functions we can see that each firm will choose the minimum quality level possible in order to maximize profits. Since Firm 2 must achieve a quality level of at least s_{min} to receive the label this will be its level of quality, while Firm 1 will make no investment in quality and produce a product of quality 0. Table 7.5 summarizes the price, quality, quantity, and profits for each firm.

Since Firm 2 must be able to make a positive profit to choose to label this places a restriction on the possible cost of the label.

$$\Pi_2 > 0 \tag{7.66a}$$

$$\frac{4\bar{\theta} s_h^2 (s_h - s_l)}{(4s_h - s_l)^2} - \alpha s_{min}^2 - L > 0 \tag{7.66b}$$

$$\frac{4\bar{\theta} s_h^2 (s_h - s_l)}{(4s_h - s_l)^2} - \alpha s_{min}^2 > L \tag{7.66c}$$

Assuming that this inequality is satisfied and Firm 2 chooses to label we can now calculate the social welfare achieved by the label. As before the social welfare is equal to the sum of the total consumer surplus, producer surplus, and the societal benefit of the emissions reduction. Total emission reduction, E, is given by the following expression:

$$E = q_1 s_1 + q_2 s_2 \tag{7.67a}$$

$$= \frac{s_h}{4s_h - s_l} \times 0 + \frac{2s_h}{4s_h - s_l} \times s_{min} \tag{7.67b}$$

$$= \frac{2s_h s_{min}}{4s_h - s_l} \tag{7.67c}$$

The consumer surplus is given by the difference between what consumers would be willing to pay for the product and what they did pay. The consumer surplus for consumers that purchase from Firm 1 is given by:

$$CS_{1=} q_1 \left(\frac{\hat{\theta}_{01} + \hat{\theta}_{12}}{2} s_l - p_1\right) \tag{7.68a}$$

$$= \frac{s_h}{4s_h - s_l} \left(\frac{\frac{\bar{\theta}(s_h - s_l)}{4s_h - s_l} + \frac{\bar{\theta}(2s_h - s_l)}{4s_h - s_l}}{2} \times s_l - \frac{\bar{\theta} s_l (s_h - s_l)}{4s_h - s_l} \right) \tag{7.68b}$$

$$= \frac{\bar{\theta} s_h^2 s_l}{2(4s_h - s_l)^2} \tag{7.68c}$$

$$= \frac{\bar{\theta} s_h^2 s_l}{2(4s_h - s_l)^2} \tag{7.68d}$$

And that of the consumers that purchase from Firm 2 is:

$$CS_2 = q_2 \left(\frac{\hat{\theta}_{12} + \bar{\theta}}{2} s_h - p_2\right) \tag{7.69a}$$

$$= \frac{2s_h}{4s_h - s_l} \left(\frac{\frac{\bar{\theta}(2s_h - s_l)}{4s_h - s_l} + \bar{\theta}}{2} \times s_h - \frac{2\bar{\theta} s_h (s_h - s_l)}{4s_h - s_l} \right) \tag{7.69b}$$

$$= \frac{2\bar{\theta} s_h^2 (s_h + s_l)}{(4s_h - s_l)^2} \tag{7.69c}$$

With the producer surplus given by the profits from each firm shown in Table 7.5, we can write the total social welfare as:

$$SW = CS_1 + CS_2 + \Pi_1 + \Pi_2 + \rho E \tag{7.70a}$$

$$= \frac{\bar{\theta} s_h^2 s_l}{2(4s_h - s_l)^2} + \frac{2\bar{\theta} s_h^2 (s_h + s_l)}{(4s_h - s_l)^2} + \frac{\bar{\theta} s_l s_h (s_h - s_l)}{(4s_h - s_l)^2} + \frac{4\bar{\theta} s_h^2 (s_h - s_l)}{(4s_h - s_l)^2} - \alpha s_{min}^2 - L + \rho \frac{2 s_h s_{min}}{4s_h - s_l} \tag{7.70b}$$

$$= \frac{\bar{\theta} s_h (12 s_h^2 - s_h s_l - 2 s_l^2)}{2(4s_h - s_l)^2} - \alpha s_{min}^2 - L + \rho \frac{2 s_h s_{min}}{4s_h - s_l} \tag{7.70c}$$

Given this expression for the total social welfare we now consider the actions of the labeling authority. Unlike the case of a continuous label, where the firms choose their level of quality over any possible value, in the case of a discrete label the authority that creates the label has the ability to choose the standards needed to receive the label. Like Ben Youssef and Lahmandi-Ayed (2008), we assume the goal of the label creator is to increase social welfare by choosing a quality level, s_{min}, such that social welfare is maximized. The optimal choice of minimum label quality is given by:

$$\frac{\partial SW}{\partial s_{min}} = 0 \Rightarrow -2\alpha s_{min}^* + \frac{2\rho s_h}{4s_h - s_l} = 0 \tag{7.71a}$$

$$\Rightarrow s_{min}^* = \frac{\rho s_h}{\alpha (4s_h - s_l)} \tag{7.71b}$$

This puts the following requirement on the cost of the label so that Firm 2 will still earn a positive profit and choose to label:

$$\frac{s_h^2 \left(4\bar{\theta}\alpha (s_h - s_l) - \rho^2\right)}{\alpha (4s_h - s_l)^2} > L \tag{7.72}$$

If the firm is not able to earn a profit with this level of quality, then the labeling authority should choose the maximum level of quality possible that still results in positive profit, as $\frac{\partial SW}{\partial s_{min}} > 0$ for values below the optimal level. Provided the optimal quality choice is feasible, we get the following expression for the total social welfare:

$$
\begin{aligned}
SW =& CS_1 + CS_2 + \Pi_1 + \Pi_2 + \rho E && (7.73a)\\
=& \frac{\overline{\theta} s_h \left(12 s_h^2 - s_h s_l - 2 s_l^2\right)}{2(4 s_h - s_l)^2} - \alpha \left(\frac{\rho s_h}{\alpha \left(4 s_h - s_l\right)}\right)^2 - L + \rho \frac{2 s_h}{4 s_h - s_l} \left(\frac{\rho s_h}{\alpha \left(4 s_h - s_l\right)}\right) && (7.73b)\\
=& \frac{\overline{\theta} s_h \left(12 s_h^2 - s_h s_l - 2 s_l^2\right)}{2(4 s_h - s_l)^2} + \frac{\rho^2 s_h^2}{\alpha \left(4 s_h - s_l\right)^2} - L && (7.73c)\\
=& \frac{\overline{\theta} \alpha s_h \left(12 s_h^2 - s_h s_l - 2 s_l^2\right) + 2 \rho^2 s_h^2}{2\alpha(4 s_h - s_l)^2} - L && (7.73d)
\end{aligned}
$$

This assumes that the quality perceived by consumer is exogenous, and not influenced by the labeling authority. If we instead assume that the choice of quality level by the labeling authority affects the quality perceived by the consumer, then we obtain a different result. In order to provide a method of comparison with the continuous label we make the following assumptions. First, the labeling authority again sets the minimum quality level needed to obtain the certification label, but now we assume the quality perceived by the consumer is equal to the minimum quality chosen by the labeling authority, $s_h = s_{min}$. Second, we again set the perceived quality of the unlabeled product to a factor λ times that of the labeled product, such that $s_l = \lambda s_h$. With these assumptions in place we can obtain the following expression for the social welfare:

$$
\begin{aligned}
SW =& \frac{\overline{\theta} s_h \left(12 s_h^2 - s_h s_l - 2 s_l^2\right)}{2(4 s_h - s_l)^2} - \alpha s_h^2 - L + \rho \frac{2 s_h^2}{4 s_h - s_l} && (7.74a)\\
=& \frac{\overline{\theta} s_h^3 \left(12 - \lambda - 2\lambda^2\right)}{2 s_h^2 (4 - \lambda)^2} - \alpha s_h^2 - L + \rho \frac{2 s_h^2}{s_h \left(4 - \lambda\right)} && (7.74b)\\
=& \frac{\overline{\theta} \left(12 - \lambda - 2\lambda^2\right) + 4\rho \left(4 - \lambda\right)}{2(4 - \lambda)^2} s_h - \alpha s_h^2 - L && (7.74c)
\end{aligned}
$$

Solving for the optimal level of s_h gives the following expression:

$$
s_h^* = \frac{\overline{\theta} \left(12 - \lambda - 2\lambda^2\right) + 4\rho (4 - \lambda)}{4\alpha (4 - \lambda)^2} \qquad (7.75)
$$

The labeling authority should then set $s_{min} = s_h^*$ and achieve a level of social welfare given

Parameter	Firm 1	Firm 2
Price (p)	$\frac{\bar{\theta}(1-\lambda)\lambda\left[\bar{\theta}\left(12-\lambda-2\lambda^2\right)+4\rho(4-\lambda)\right]}{4\alpha(4-\lambda)^3}$	$\frac{2\bar{\theta}(1-\lambda)\left[\bar{\theta}\left(12-\lambda-2\lambda^2\right)+4\rho(4-\lambda)\right]}{4\alpha(4-\lambda)^3}$
Quality (s)	0	$\frac{\bar{\theta}\left(12-\lambda-2\lambda^2\right)+4\rho(4-\lambda)}{4\alpha(4-\lambda)^2}$
Quantity (q)	$\frac{1}{4-\lambda}$	$\frac{2}{4-\lambda}$
Profit (Π)	$\frac{\bar{\theta}(1-\lambda)\lambda\left[\bar{\theta}\left(12-\lambda-2\lambda^2\right)+4\rho(4-\lambda)\right]}{4\alpha(4-\lambda)^4}$	$\frac{16\bar{\theta}(1-\lambda)\left[\bar{\theta}\left(12-\lambda-2\lambda^2\right)+4\rho(4-\lambda)\right]-\left[\bar{\theta}\left(12-\lambda-2\lambda^2\right)+4\rho(4-\lambda)\right]^2}{16\alpha(4-\lambda)^4} - L$

Table 7.6: Summary of Discrete Labeling Results with Endogenous Quality Perception

by:

$$SW^* = \frac{\left[\bar{\theta}\left(12-\lambda-2\lambda^2\right)+4\rho(4-\lambda)\right]^2}{16\alpha(4-\lambda)^4} - L \tag{7.76}$$

This is subject to the condition that Firm 2 must choose to label, so its profit must be greater than zero:

$$\Pi_2 > 0 \tag{7.77a}$$

$$\frac{4\bar{\theta}s_h^3(1-\lambda)}{s_h^2(4-\lambda)^2} - \alpha s_h^2 - L > 0 \tag{7.77b}$$

$$\frac{16\bar{\theta}(1-\lambda)\left[\bar{\theta}\left(12-\lambda-2\lambda^2\right)+4\rho(4-\lambda)\right]-\left[\bar{\theta}\left(12-\lambda-2\lambda^2\right)+4\rho(4-\lambda)\right]^2}{16\alpha(4-\lambda)^4} > L \tag{7.77c}$$

The results are summarized in Table 7.6.

7.5.1 Label Comparison

With the outcome of each labeling scheme solved we can now compare the performance achieved by both labels.

Proposition 7.4. *The social welfare achieved by the discrete label is always higher than that of the continuous label when the optimal choice of the minimum quality standard is feasible.*

Proof. Let SW_{c2} denote the level of social welfare achieved using the continuous label when both firms choose to label

$$SW_{c2} = \frac{\bar{\theta}}{\alpha}\left(.034559\bar{\theta} + .07282\rho\right) - 2L \tag{7.78}$$

And let SW_d be that of the discrete label:

$$SW_d = \frac{\left[\bar{\theta}\left(12-\lambda-2\lambda^2\right)+4\rho(4-\lambda)\right]^2}{16\alpha(4-\lambda)^4} - L \tag{7.79}$$

The continuous label with both firms labeling will provide a higher social welfare provided the following expression is true:

$$SW_{c2} > SW_d \tag{7.80a}$$

$$\frac{\bar{\theta}}{\alpha}\left(.03459\bar{\theta}+.07282\rho\right) - 2L > \frac{\left[\bar{\theta}\left(12-\lambda-2\lambda^2\right)+4\rho(4-\lambda)\right]^2}{16\alpha(4-\lambda)^4} - L \tag{7.80b}$$

Rearranging the terms this expression is true provided:

$$\frac{\bar{\theta}^2}{\alpha}\left[.03459 - \frac{\left(12-\lambda-2\lambda^2\right)^2}{16\left(4-\lambda\right)^4}\right] + \frac{\rho\bar{\theta}}{\alpha}\left[.07282 - \frac{\left(12-\lambda-2\lambda^2\right)}{2\left(4-\lambda\right)^3}\right] - \frac{\rho^2}{\alpha\left(4-\lambda\right)^2} > L \tag{7.80c}$$

Over the range of possible values for λ all three terms on the left hand side will be negative, and thus no possible value of L will result in a higher social welfare for the continuous label. Since social welfare is always higher in the case where both firms label than when only one firm chooses to label, the social welfare provided by the discrete label is always higher than that of the continuous label. □

In this case the actions of the labeling authority generally come at the expense of the profits of the high quality firm. By setting the minimum quality standard higher than the firm would otherwise choose, the firm's profits are reduced but total social welfare is increased due to the higher level of emissions reductions. Let Π_{1c} and Π_{2c} represent the profits for the high quality firm under the continuous label when it is the only firm to label and when both firms label, respectively. The high quality firm earns higher profits under the continuous label provided:

$$\Pi_{c2} > \Pi_d \tag{7.81a}$$

$$\frac{16\bar{\theta}^2\mu^3(4\mu^2-3\mu+2)(4\mu-7)}{4\alpha(4\mu-1)^6}-L> \frac{\left[\bar{\theta}\left(2\lambda^2-15\lambda+4\right)-\rho\left(16-4\lambda\right)\right]\left[\bar{\theta}\left(12-\lambda-2\lambda^2\right)+4\rho(4-\lambda)\right]}{16\alpha(4-\lambda)^4}-L \quad (7.81b)$$

Rearranging terms produces the following condition that must be true for the firm to earn higher profits under the continuous label:

$$\frac{\bar{\theta}^2}{\alpha}\left[.00076+\frac{\left(12-\lambda-2\lambda^2\right)^2-16\left(1-\lambda\right)\left(12-\lambda-2\lambda^2\right)}{16\left(4-\lambda\right)^4}\right] +\frac{\rho\bar{\theta}}{\alpha}\left[\frac{8\left(12-\lambda-2\lambda^2\right)^2-64\left(1-\lambda\right)}{16\left(4-\lambda\right)^3}\right]+\frac{\rho^2}{\alpha\left(4-\lambda\right)^2}>0 \quad (7.81c)$$

The expression on the left hand side is negative only for the case where λ is very low and $\bar{\theta} \gg \rho$. In those situations the existence of the discrete label actually helps protect the high quality firm, as in the continuous label scenario the low quality firm would normally choose to also label its product, resulting in increased price competition. In all other cases the cost of complying with the high minimum quality standard eats into the profits of the high quality firm. Further, the high quality firm will earn higher profits under the continuous label when it is the only firm to label provided:

$$\Pi_{c1} > \Pi_d \quad (7.82a)$$

$$\frac{4\bar{\theta}^2(1-\lambda)^2}{\alpha(4-\lambda)^4}-L > \frac{16\bar{\theta}\left(1-\lambda\right)\left[\bar{\theta}\left(12-\lambda-2\lambda^2\right)+4\rho(4-\lambda)\right]-\left[\bar{\theta}\left(12-\lambda-2\lambda^2\right)+4\rho(4-\lambda)\right]^2}{16\alpha(4-\lambda)^4}-L \quad (7.82b)$$

Rearranging the terms this is true provided:

$$\frac{\bar{\theta}^2}{\alpha}\left[\frac{4\,(1-\lambda)^2}{(4-\lambda)^4}+\frac{(12-\lambda-2\lambda^2)^2}{16\,(4-\lambda)^4}-\frac{(1-\lambda)\,(12-\lambda-2\lambda^2)}{(4-\lambda)^4}\right] + \frac{\rho\bar{\theta}}{\alpha}\left[\frac{8\,(12-\lambda-2\lambda^2)^2-64\,(1-\lambda)}{16\,(4-\lambda)^3}\right]+\frac{\rho^2}{\alpha\,(4-\lambda)^2}>0 \quad (7.82c)$$

Each term on the left hand side is positive for all values of λ, and thus the high quality firm always earns greater profits under the continuous labeling scheme than the discrete scheme if it is the only firm that labels. Under our model the price competition between the firms is identical in this scenario, but under the discrete label Firm 2 is forced to choose a higher level of quality than it prefers, reducing profits.

7.5.2 Discussion

In this section we provided an example of a standard Type I certification style eco-label that could be used to certify low carbon products. Our results show that, provided the labeling authority is able to choose an optimal minimum level of quality that still induces the high quality firm to label, the discrete label will produce a higher level of social welfare than the continuous label. This is due to strategic behavior on the part of the labeling authority that allows them to choose a minimum level of quality that maximizes social welfare, unlike the continuous label where the firms choose the level of quality in order to maximize profits. This increase in social welfare generally comes at the expense of firm profits, as the high quality firm usually earns higher profits under the continuous labeling scheme. From the firm perspective the use of a discrete label may be less preferable than the continuous label. However, if consumers show a better understanding of the simpler discrete labels then this could provide motivation for a switch from ineffective continuous labels.

7.6 Two-tier Supply Chain Model

While the decision to label a product with a carbon label for sale to the end consumer may ultimately rest with one firm, the actual carbon footprint of the product is dependent on all the firms in the supply chain. To consider the implications of this fact, and the role of carbon labels in reducing emissions throughout the supply chain, we now extend our basic carbon label model to a two-tier supply chain through the inclusion an upstream supplier. We recognize that in practice the basic model and the two-tier supply chain model are reflections of the same supply chain structure. That is, though we refer to the basic model as the single firm scenario, that firm still operates as a member of a supply chain. We refer to it as the single firm scenario because in the decision to reduce the carbon footprint and label the product the firm acts alone. This is similar to the current state of affairs where a single firm conducts an LCA of the supply chain, labels its product, incurs the associated costs, and reaps the potential benefits. By acting alone the firm forgoes two possible benefits from collaboration with its supply chain partners.

First, by conducting the LCA of the supply chain on its own the firm incurs all the associated costs. We previously identified the cost of labeling to be composed of two factors, the cost to actually perform the measurement and the cost paid to a third party to certify the label. In both the single firm case and the two-stage supply chain the work required to measure the carbon footprint is the same—that of performing an LCA for the entire supply chain. In the single firm case all of the costs are born by one firm, while in the two-stage supply chain the costs are split between the firms. If the upstream supplier were to provide the carbon footprint information of its product to the downstream firm through a B2B carbon label, this would reduce the work required by the downstream firm and possibly reduce its cost to label.

Second, if the downstream firm measures the carbon footprint of its product on its own without input from the upstream supplier it misses the opportunity to have the upstream supplier also contribute to reductions in the carbon footprint. By providing the actual carbon footprint of the component it supplies to the downstream firm through the use of a B2B label, the upstream firm can work to reduce that carbon footprint, resulting in a decrease in the carbon footprint of the final product sold by the downstream firm. If the downstream firm does not use actual data from the upstream supplier, and instead relies on standard LCA techniques to estimate the impact of upstream production, then efficiency improvements made by the supplier will not impact the calculated carbon footprint.

As in the basic, single-tier model we consider the amount of emissions reduced to be a measure of product quality, but now we define the quality of product i to be $s_i = s_{iu} + s_{id}$ where s_{iu} is the emissions reduced by the upstream supplier and s_{id} is the emissions reduced by the downstream firm. We normalize the production process such that each unit of output sold to the end consumer requires one unit of input from the upstream supplier.

As before the downstream firm is able to invest in processes to reduce emissions with a fixed cost of αs_{id}^2 per unit of emissions reduction. Similarly, the upstream supplier also faces a quadratic fixed cost of βs_{iu}^2 to reduce emissions. The downstream firm purchases the upstream input at a wholesale price of w_i per unit and then sets the final price, p_i for sale to the end consumer. Consumers base the purchasing decision on the end price of the product and the total product quality. With these assumptions in place the respective profit functions, without accounting for the cost of the label, for the upstream supplier and downstream firm are given below.

$$\Pi_{1d} = (p_1 - w_1)q_1 - \alpha s_{1d}^2 = \frac{p_1 - w_1}{\bar{\theta}}\left(\frac{p_2 - p_1}{(s_{2d} + s_{2u}) - (s_{1d} + s_{1u})} - \frac{p_1}{s_{1d} + s_{1u}}\right) - \alpha s_{1d}^2 \quad (7.83)$$

$$\Pi_{1u} = w_1 q_1 - \beta s_{1u}^2 = \frac{w_1}{\bar{\theta}}\left(\frac{p_2 - p_1}{(s_{2d} + s_{2u}) - (s_{1d} + s_{1u})} - \frac{p_1}{s_{1d} + s_{1u}}\right) - \beta s_{1u}^2 \quad (7.84)$$

$$\Pi_{2d} = (p_2 - w_2)q_2 - \alpha s_{2d}^2 = \frac{p_2 - w_2}{\bar{\theta}}\left(\bar{\theta} - \frac{p_2 - p_1}{(s_{2d} + s_{2u}) - (s_{1d} + s_{1u})}\right) - \alpha s_{2d}^2 \quad (7.85)$$

$$\Pi_{2u} = w_2 q_2 - \beta s_{2u}^2 = \frac{w_2}{\bar{\theta}}\left(\bar{\theta} - \frac{p_2 - p_1}{(s_{2d} + s_{2u}) - (s_{1d} + s_{1u})}\right) - \beta s_{2u}^2 \quad (7.86)$$

If the upstream supplier chooses to produce at a quality level greater than zero it must invest in a label to certify the quality level. Let L_u be the fixed cost for the upstream firm to label. An unlabeled product produced by the upstream supplier is assumed to be of zero quality. If the downstream firm wishes to communicate the quality of the product to the end consumer it must also invest in a label. Let L_d be the fixed cost for the downstream firm to label. The label value will communicate the sum of the downstream firm quality and the upstream supplier quality, provided the supplier invested in a label. An unlabeled product sold to end consumers again has quality equal to λs_2. Once again there are four possible scenarios for the final product. First, we analyze Scenario 2, where both products are labeled, and next Scenario 3, where only the high quality product is labeled.

As we are interested in the effect of including the upstream supplier in the labeling decision we consider the two-tier model in the case of a vertically integrated channel with one decision maker. In this manner we can determine what should be the optimal decision for the supply chain as a whole, and contrast this with the outcome when a single firm acts alone. We refer to this as the supply chain scenario, because the costs, benefits, and outcomes can be influenced by both the upstream supplier and the downstream firm.

7.6.1 Both End Products are Labeled

The profits of the supply chain as a whole, assuming both the upstream supplier and downstream firm choose to label, are given by:

$$\Pi_1 = p_1 q_1 - \alpha s_{1d}^2 - \beta s_{1u}^2 = \frac{p_1}{\bar{\theta}} \left(\frac{p_2 - p_1}{s_2 - s_1} - \frac{p_1}{s_1} \right) - \alpha s_{1d}^2 - -\beta s_{1u}^2 - L_u - L_d \tag{7.87}$$

$$\Pi_2 = p_2 q_2 - \alpha s_{2d}^2 - \beta s_{2u}^2 = \frac{p_2}{\bar{\theta}} \left(\bar{\theta} - \frac{p_2 - p_1}{s_2 - s_1} \right) - \alpha s_{2d}^2 - -\beta s_{2u}^2 - L_u - L_d \tag{7.88}$$

We note that the second stage price game is unchanged from the single firm case, and thus the optimal prices as a function of the total supply chain quality are:

$$p_1 = \frac{\bar{\theta} s_1 (s_2 - s_1)}{4 s_2 - s_1} \tag{7.89}$$

$$p_2 = \frac{2 \bar{\theta} s_2 (s_2 - s_1)}{4 s_2 - s_1} \tag{7.90}$$

These give the following profits as a function of total supply chain quality:

$$\Pi_1 (s_{1d}, s_{1u}, s_{2d}, s_{2u}) = \frac{\bar{\theta} s_1 s_2 (s_2 - s_1)}{(4 s_2 - s_1)^2} - \alpha s_{1d}^2 - \beta s_{1u}^2 - L_u - L_d \tag{7.91}$$

$$\Pi_2 (s_{1u}, s_{1d}, s_{2u}, s_{2d}) = \frac{4 \bar{\theta} s_2^2 (s_2 - s_1)}{(4 s_2 - s_1)^2} - \alpha s_{2d}^2 - \beta s_{2u}^2 - L_u - L_d \tag{7.92}$$

Differentiating each profit function with respect to the upstream and downstream quality choices gives the following expressions:

$$\frac{\partial \Pi_1}{\partial s_{1d}} = 0 \Rightarrow \frac{\overline{\theta} s_2^2 - 2\overline{\theta} s_1 s_2}{(4s_2 - s_1)^2} + \frac{2\overline{\theta} s_1 s_2^2 (s_2 - s_1)}{(4s_2 - s_1)^3} - 2\alpha s_{1d} = 0 \tag{7.93}$$

$$\frac{\partial \Pi_1}{\partial s_{1u}} = 0 \Rightarrow \frac{\overline{\theta} s_2^2 - 2\overline{\theta} s_1 s_2}{(4s_2 - s_1)^2} + \frac{2\overline{\theta} s_1 s_2^2 (s_2 - s_1)}{(4s_2 - s_1)^3} - 2\beta s_{1u} = 0 \tag{7.94}$$

$$\frac{\partial \Pi_2}{\partial s_{2d}} = 0 \Rightarrow \frac{12\overline{\theta} s_2^2 - 8\overline{\theta} s_1 s_2}{(4s_2 - s_1)^2} - \frac{32\overline{\theta} s_2^2 (s_2 - s_1)}{(4s_2 - s_1)^3} - 2\alpha s_{2d} = 0 \tag{7.95}$$

$$\frac{\partial \Pi_2}{\partial s_{2u}} = 0 \Rightarrow \frac{12\overline{\theta} s_2^2 - 8\overline{\theta} s_1 s_2}{(4s_2 - s_1)^2} - \frac{32\overline{\theta} s_2^2 (s_2 - s_1)}{(4s_2 - s_1)^3} - 2\beta s_{2u} = 0 \tag{7.96}$$

Rearranging the terms gives the following expressions for the optimal quality choices of the upstream supplier and downstream firm in each supply chain:

$$s_{1d} = \frac{\bar{\theta} s_2^2 (4s_2 - 7s_1)}{2\alpha (4s_2 - s_1)^3} \tag{7.97}$$

$$s_{1u} = \frac{\bar{\theta} s_2^2 (4s_2 - 7s_1)}{2\beta (4s_2 - s_1)^3} \tag{7.98}$$

$$s_{2d} = \frac{4\bar{\theta} s_2 (4s_2^2 - 3s_1 s_2 + 2s_1^2)}{2\alpha (4s_2 - s_1)^3} \tag{7.99}$$

$$s_{2u} = \frac{4\bar{\theta} s_2 (4s_2^2 - 3s_1 s_2 + 2s_1^2)}{2\beta (4s_2 - s_1)^3} \tag{7.100}$$

Again defining $s_2 = \mu s_1$ and adding the respective upstream and downstream qualities, we get the same result as before, with one solution of $\mu \approx 5.2512$. The resulting quality levels are then:

$$s_{1d} = \frac{\bar{\theta} \mu^2 (4\mu - 7)}{2\alpha (4\mu - 1)^3} \tag{7.101}$$

$$s_{1u} = \frac{\bar{\theta} \mu^2 (4\mu - 7)}{2\beta (4\mu - 1)^3} \tag{7.102}$$

$$s_{2d} = \frac{4\bar{\theta} \mu (4\mu^2 - 3\mu + 2)}{2\alpha (4\mu - 1)^3} \tag{7.103}$$

Parameter	Supply Chain 1	Supply Chain 2
Price (p)	$\frac{\alpha+\beta}{\alpha\beta}\frac{\bar{\theta}^2\mu^2(4\mu-7)(\mu-1)}{2(4\mu-1)^4}$	$\frac{\alpha+\beta}{\alpha\beta}\frac{4\bar{\theta}^2\mu(4\mu^2-3\mu+2)(\mu-1)}{(4\mu-1)^4}$
Total Quality (s)	$\frac{\alpha+\beta}{\alpha\beta}\frac{\bar{\theta}\mu^2(4\mu-7)}{2(4\mu-1)^3}$	$\frac{\alpha+\beta}{\alpha\beta}\frac{2\bar{\theta}\mu(4\mu^2-3\mu+2)}{(4\mu-1)^3}$
Upstream Quality (s_u)	$\frac{\bar{\theta}\mu^2(4\mu-7)}{2\beta(4\mu-1)^3}$	$\frac{2\bar{\theta}\mu(4\mu^2-3\mu+2)}{\beta(4\mu-1)^3}$
Downstream Quality (s_d)	$\frac{\bar{\theta}\mu^2(4\mu-7)}{2\alpha(4\mu-1)^3}$	$\frac{2\bar{\theta}\mu(4\mu^2-3\mu+2)}{\alpha(4\mu-1)^3}$
Quantity (q)	$\frac{\mu}{(4\mu-1)}$	$\frac{2\mu}{(4\mu-1)}$
Profit (Π)	$\frac{\alpha+\beta}{\alpha\beta}\frac{\bar{\theta}^2\mu^3(4\mu-7)(4\mu^2-3\mu+2)}{4(4\mu-1)^6} - L_u - L_d$	$\frac{\alpha+\beta}{\alpha\beta}\frac{4\bar{\theta}^2\mu^3(4\mu^2-3\mu+2)(4\mu-7)}{(4\mu-1)^6} - L_u - L_d$

Table 7.7: Summary of Supply Chain Scenario 2

$$s_{2u} = \frac{4\bar{\theta}\mu\,(4\mu^2 - 3\mu + 2)}{2\beta(4\mu - 1)^3} \tag{7.104}$$

And the total quality for each supply chain is given by:

$$s_1 = \frac{\alpha + \beta}{\alpha\beta}\frac{\bar{\theta}\mu^2\,(4\mu - 7)}{2(4\mu - 1)^3} \tag{7.105}$$

$$s_2 = \frac{\alpha + \beta}{\alpha\beta}\frac{4\bar{\theta}\mu\,(4\mu^2 - 3\mu + 2)}{2(4\mu - 1)^3} \tag{7.106}$$

We can now determine the resulting profit, quality, quantity, and prices for each supply chain. Both supply chains choose positive quality for both the upstream supplier and downstream firm, and thus incur charges of L_u and L_d in order to obtain certified labels. The results are shown in Table 7.7.

7.6.2 Only One End Product is Labeled

In this scenario the unlabeled product once again is assumed to be of quality λs_2 by the consumer. This produces the following expressions for the profit of each supply chain:

$$\Pi_1 = p_1 q_1 - \alpha s_{1d}^2 - \beta s_{1u}^2 = \frac{p_1}{\bar{\theta}}\left(\frac{p_2 - p_1}{s_2 - \lambda s_2} - \frac{p_1}{\lambda s_2}\right) - \alpha s_{1d}^2 - \beta s_{1u}^2 \tag{7.107}$$

$$\Pi_2 = p_2 q_2 - \alpha s_{2d}^2 - \beta s_{2u}^2 = \frac{p_2}{\bar{\theta}}\left(\bar{\theta} - \frac{p_2 - p_1}{s_2 - \lambda s_2}\right) - \alpha s_{2d}^2 - \beta s_{2u}^2 - L_u - L_d \tag{7.108}$$

Following the same process as in section 7.4.3, we obtain the following expressions for the prices:

$$p_1 = \frac{\bar{\theta} s_2 \lambda (1-\lambda)}{4-\lambda} \tag{7.109}$$

$$p_2 = \frac{2\bar{\theta} s_2 (1-\lambda)}{4-\lambda} \tag{7.110}$$

These give the following profits as a function of total supply chain quality:

$$\Pi_1 = \frac{p_1}{\bar{\theta}}\left(\frac{p_2 - p_1}{s_2 - \lambda s_2} - \frac{p_1}{\lambda s_2}\right) - \alpha s_{1d}^2 - \beta s_{1u}^2 = \frac{\bar{\theta} s_2 \lambda (1-\lambda)}{(4-\lambda)^2} - \alpha s_{1d}^2 - \beta s_{1u}^2 \tag{7.111}$$

$$\Pi_2 = \frac{p_2}{\bar{\theta}}\left(\bar{\theta} - \frac{p_2 - p_1}{s_2 - \lambda s_2}\right) - \alpha s_{2d}^2 - \beta s_{2u}^2 = \frac{4\bar{\theta} s_2 (1-\lambda)}{(4-\lambda)^2} - \alpha s_{2d}^2 - \beta s_{2u}^2 - L_u - L_d \tag{7.112}$$

Differentiating each profit function with respect to the upstream and downstream quality choices gives the following expressions:

$$\frac{\partial \Pi_1}{\partial s_{1d}} = 0 \Rightarrow -2\alpha s_{1d} = 0 \tag{7.113}$$

$$\frac{\partial \Pi_1}{\partial s_{1u}} = 0 \Rightarrow -2\beta s_{1u} = 0 \tag{7.114}$$

$$\frac{\partial \Pi_2}{\partial s_{2d}} = 0 \Rightarrow \frac{4\bar{\theta}\,(1-\lambda)}{(4-\lambda)^2} - 2\alpha s_{2d} = 0 \tag{7.115}$$

$$\frac{\partial \Pi_2}{\partial s_{2u}} = 0 \Rightarrow \frac{4\bar{\theta}\,(1-\lambda)}{(4-\lambda)^2} - 2\beta s_{2u} = 0 \tag{7.116}$$

Solving these equations for the quality values we are now able to solve for the price, quality, quantity, and profit for each supply chain. Only the high quality supply chain labels, and by choosing positive quality levels both upstream and downstream it incurs charges of L_u and L_d to obtain the labels. As the low quality supply chain does not label or invest in quality improvements, the downstream firm will choose to purchase an undifferentiated product of quality zero at price zero from its upstream supplier. Thus, the upstream supplier in the low quality supply chain will earn zero profit, and any profit for the supply chain is captured by the downstream firm. The results are shown in Table 7.8.

Parameter	Supply Chain 1	Supply Chain 2
Price (p)	$\frac{\alpha+\beta}{\alpha\beta}\frac{2\theta^2\lambda(1-\lambda)^2}{(4-\lambda)^3}$	$\frac{\alpha+\beta}{\alpha\beta}\frac{4\theta^2(1-\lambda)^2}{(4-\lambda)^3}$
Total Quality (s)	0	$\frac{\alpha+\beta}{\alpha\beta}\frac{2\theta(1-\lambda)}{(4-\lambda)^2}$
Downstream Quality (s_d)	0	$\frac{2\theta(1-\lambda)}{\alpha(4-\lambda)^2}$
Upstream Quality (s_u)	0	$\frac{2\theta(1-\lambda)}{\beta(4-\lambda)^2}$
Quantity (q)	$\frac{1}{4-\lambda}$	$\frac{2}{4-\lambda}$
Profit (Π)	$\frac{\alpha+\beta}{\alpha\beta}\frac{2\theta^2\lambda(1-\lambda)^2}{(4-\lambda)^4}$	$\frac{\alpha+\beta}{\alpha\beta}\frac{4\theta^2(1-\lambda)^2}{(4-\lambda)^4} - L_u - L_d$

Table 7.8: Summary of Supply Chain Scenario 3

7.6.3 Comparison to the Single Firm Scenario

In comparing the single firm model and the supply chain model we note that the quality chosen by the downstream firm is identical under the same labeling outcome. That is, the level of quality chosen by the downstream firm is unaffected by the presence of the upstream supplier given identical labeling outcomes for the two products. However, total product quality is increased through the additional quality provided by the upstream firm. The increased quality of the final product is reflected in the higher price premium charged by the downstream firm to the end consumer. In all cases the price and total quality of the final product for the two-tier supply chain is equal to $\frac{\alpha+\beta}{\beta}$ times that of the single-tier case where the downstream firm acts alone. Because the quantity sold is dependent on the ratio of price to quality, the proportional increases result in the sales quantity for each product being identical to the single-tier case. This results in profits, exclusive of the cost to label, again being $\frac{\alpha+\beta}{\beta}$ times the profits of the single-tier case. Of special interest is that both the upstream supplier and the downstream firm choose a quality level such that the marginal cost of quality is identical. This is a reflection of Coase's Equimarginal Principle, which states that the most efficient method for reducing pollution is for every firm to reduce emissions to the level where all marginal costs of reduction are equal.

Next, we examine the conditions for the label that result in greater profit for the supply chain as a whole compared to the single firm case. In order for the supply chain to achieve higher profits than the single firm case any additional labeling costs must be offset by the increase in profits from the higher price premium and quality level. Beginning with the scenario where both products are labeled we have the following condition for the channel profits to be greater than the single firm case for the low quality supply chain:

$$\frac{\alpha+\beta}{\alpha\beta}\frac{\overline{\theta}^2\mu^3(4\mu-7)(4\mu^2-3\mu+2)}{4(4\mu-1)^6} - L_u - L_d > \frac{\overline{\theta}^2\mu^3(4\mu-7)(4\mu^2-3\mu+2)}{4\alpha(4\mu-1)^6} - L \quad (7.117)$$

And for the high quality supply chain:

$$\frac{\alpha+\beta}{\alpha\beta}\frac{4\overline{\theta}^2\mu^3(4\mu^2-3\mu+2)(4\mu-7)}{(4\mu-1)^6} - L_u - L_d > \frac{4\overline{\theta}^2\mu^3(4\mu^2-3\mu+2)(4\mu-7)}{\alpha(4\mu-1)^6} - L \quad (7.118)$$

Rearranging terms gives the following condition regarding the cost of the label for the supply chain to earn greater profits than the single firm case for the low quality supply chain:

$$\frac{1}{\beta}\frac{\overline{\theta}^2\mu^3(4\mu-7)(4\mu^2-3\mu+2)}{4(4\mu-1)^6} > (L_u + L_d) - L \quad (7.119)$$

And for the high quality supply chain:

$$\frac{1}{\beta}\frac{4\overline{\theta}^2\mu^3(4\mu^2-3\mu+2)(4\mu-7)}{(4\mu-1)^6} > (L_u + L_d) - L \quad (7.120)$$

The requirement for the supply chain scenario to result in greater profit is simply that the increase in profits from the inclusion of the upstream firm must offset any addition in cost due to the requirement of two labels. Looking at the profits for the case where only the high quality product is labeled we have the following expression for the low quality supply chain to earn greater profits than in the single firm case:

$$\frac{\alpha+\beta}{\alpha\beta}\frac{2\bar{\theta}^2\lambda(1-\lambda)^2}{(4-\lambda)^4} > \frac{2\bar{\theta}^2\lambda(1-\lambda)^2}{\alpha(4-\lambda)^4} \quad (7.121)$$

And for the high quality supply chain:

$$\frac{\alpha+\beta}{\alpha\beta}\frac{4\bar{\theta}^2(1-\lambda)^2}{(4-\lambda)^4} - L_u - L_d > \frac{4\bar{\theta}^2(1-\lambda)^2}{\alpha(4-\lambda)^4} - L \quad (7.122)$$

Which gives the following condition for the low quality supply chain:

$$\frac{1}{\beta}\frac{2\bar{\theta}^2\lambda(1-\lambda)^2}{(4-\lambda)^4} > 0 \tag{7.123}$$

And for the high quality supply chain:

$$\frac{1}{\beta}\frac{4\bar{\theta}^2(1-\lambda)^2}{(4-\lambda)^4} > (L_u + L_d) - L \tag{7.124}$$

We can see that the high quality firm again faces the same requirement that the value added by the upstream firm must outweigh the additional labeling costs. As β is a positive value, the expression on the left hand side of (7.123) is always greater than or equal to zero, and the profits of the low quality supply chain will always be at least as well off. This is because when it chooses not to label the final product the low quality firm faces no increase in labeling costs, continues to purchase the zero cost product from its upstream supplier, and is able to charge a higher price due to the increase in price and quality for the product of the high quality supply chain.

Our work so far has assumed that the cost of the label was such that both the upstream and downstream firms would choose to invest in a label. Next, we consider scenarios where this may not be the case by examining the constraints on the cost of the label. To put these constraints in context we consider a range of possible values for the labeling costs of the supply chain. We consider the cost of the label to be composed of two factors, the cost to actually perform the measurement and the cost paid to a third party to certify the label. In both the single firm case and the two-stage supply chain case we consider the total cost to measure the carbon footprint to be identical. The work required in both cases is the same—that of performing an LCA for the entire supply chain. In the single firm case all of the measurement costs are born by one firm, while in the two-stage supply chain the costs are split between the firms. However, if both the upstream and downstream firm choose to label the certification costs to the supply chain will be increased, as the upstream supplier must invest to certify a B2B label and the downstream firm must certify a B2C label. Thus, the total change in labeling costs is dependent on the relationship between the measurement cost and the certification cost.

7.6.3.1 Low Certification Costs

If the certification costs are minimal compared to the cost of performing the measurement then the total combined cost for the supply chain to label is the same as for the single firm, and $L_u + L_d = L$. The conditions for the supply chain scenario to produce greater profits for the low quality supply chain when both products are labeled can then be written as:

$$\frac{1}{\beta}\frac{\overline{\theta}^2\mu^3(4\mu-7)(4\mu^2-3\mu+2)}{4(4\mu-1)^6} > 0 \tag{7.125}$$

And for the high quality supply chain as:

$$\frac{1}{\beta}\frac{4\overline{\theta}^2\mu^3(4\mu^2-3\mu+2)(4\mu-7)}{(4\mu-1)^6} > 0 \tag{7.126}$$

When only one product is labeled the condition for higher profits for the low quality supply chain is:

$$\frac{1}{\beta}\frac{2\overline{\theta}^2\lambda(1-\lambda)^2}{(4-\lambda)^4} > 0 \tag{7.127}$$

And for the high quality supply chain:

$$\frac{1}{\beta}\frac{4\overline{\theta}^2(1-\lambda)^2}{(4-\lambda)^4} > 0 \tag{7.128}$$

In this case the supply chain scenario is more efficient than the single firm scenario, as profits will always be greater provided at least one firm labels and equal when no firm labels. A summary of the labeling results under this scenario are shown in Table 7.9. As in the single firm case the labeling outcome is dependent on several special values of λ, designated by λ_0', λ_1', and λ_2'; which can be solved in a similar manner to the single firm case.

Proposition 7.5. *If the certification cost is low then the inclusion of the upstream supplier increases social welfare.*

Proof. We first note that when the same number of products are labeled the quantity of each product sold is identical between the supply chain and single firm case, and thus the product choice of any individual consumer will be unchanged. Since the quality and price of

Label Cost (L)	Perceived Quality (λ)	Supply Chain 1 Decision	Supply Chain 1 Profit	Supply Chain 2 Decision	Supply Chain 2 Profit
$0 < L < .00076\bar{\theta}^2 \frac{\alpha+\beta}{\alpha\beta}$	$\lambda < \lambda_1^{'}$ or $\lambda > \lambda_2^{'}$	Label	$\frac{\alpha+\beta}{\alpha\beta} \frac{\bar{\theta}^2 \mu^3 (4\mu-7)(4\mu^2-3\mu+2)}{4(4\mu-1)^6} - L$	Label	$\frac{\alpha+\beta}{\alpha\beta} \frac{16\bar{\theta}^2 \mu^3 (4\mu^2-3\mu+2)(4\mu-7)}{4(4\mu-1)^6} - L$
$0 < L < .00076\bar{\theta}^2 \frac{\alpha+\beta}{\alpha\beta}$	$\lambda_1^{'} < \lambda < \lambda_2^{'}$	No Label	$\frac{\alpha+\beta}{\alpha\beta} \frac{2\bar{\theta}^2 \lambda (1-\lambda)^2}{(4-\lambda)^4}$	Label	$\frac{\alpha+\beta}{\alpha\beta} \frac{4\bar{\theta}^2 (1-\lambda)^2}{(4-\lambda)^4} - L$
$.00076\bar{\theta}^2 \frac{\alpha+\beta}{\alpha\beta} < L < \frac{\bar{\theta}^2}{64} \frac{\alpha+\beta}{\alpha\beta}$	$\lambda < \lambda_0^{'}$	No Label	$\frac{\alpha+\beta}{\alpha\beta} \frac{2\bar{\theta}^2 \lambda (1-\lambda)^2}{(4-\lambda)^4}$	Label	$\frac{\alpha+\beta}{\alpha\beta} \frac{4\bar{\theta}^2 (1-\lambda)^2}{(4-\lambda)^4} - L$
$.00076\bar{\theta}^2 \frac{\alpha+\beta}{\alpha\beta} < L < \frac{\theta^2}{64} \frac{\alpha+\beta}{\alpha\beta}$	$\lambda > \lambda_0^{'}$	No Label	0	No Label	0
$L > \frac{\theta^2}{64} \frac{\alpha+\beta}{\alpha\beta}$	any	No Label	0	No Label	0

Table 7.9: Equilibrium Results with Low Certification Costs

each product is increased by a proportional amount the consumer surplus for each consumer, given by $\theta s - p$, also increases by that proportional amount. Further, given that product quantities are unchanged, but product quality is increased, the societal benefit from the emissions reduction is increased. Finally, the profits of the supply chain are increased. Together these show that given the same number of labeled products between the single firm and supply chain scenario the supply chain scenario will produce a higher total social welfare.

Next, we consider the social welfare between the case where both products are labeled and only one product is labeled. Following the same logic as in Proposition 7.2 we can see that the case with both products labeled has higher social welfare if:

$$L < \frac{\alpha+\beta}{\alpha\beta}\bar{\theta}^2\left(.03459 - \frac{2\lambda^3 - 5\lambda^2 - 5\lambda + 8}{(4-\lambda)^4}\right) + \frac{\alpha+\beta}{\alpha\beta}\bar{\theta}\rho\left(.07282 - \frac{4\lambda^2 - 20\lambda + 16}{(4-\lambda)^4}\right) \tag{7.129}$$

The right hand side reaches a minimum of $.00334\frac{\alpha+\beta}{\alpha\beta}\bar{\theta}^2 + .01032\frac{\alpha+\beta}{\alpha\beta}\bar{\theta}\rho$ at $\lambda = 0$. For both products to be labeled we must have $L < .00076\bar{\theta}^2\frac{\alpha+\beta}{\alpha\beta}$, and thus the social welfare will be higher when both products are labeled as opposed to only the high quality product.

We have now shown that social welfare is higher in the supply chain scenario than the single firm scenario provided that an equal or greater number of products are labeled, and thus total social welfare will be higher provided the inclusion of the upstream firm does not result in less products being labeled. First, by inspection the range of values of L for which products will be labeled is greater in the supply chain scenario than the single firm scenario. Next, at any given value of L and λ for which one or both products are labeled in the single firm scenario at least that many products are labeled in the supply chain scenario. Consider that if at a given value of L and λ only the high quality firm labels in the single firm scenario, then we know that the high quality firm's profit must be positive. Therefore, the following condition is true:

$$\frac{1}{\alpha}\frac{4\bar{\theta}^2(1-\lambda)^2}{(4-\lambda)^4} - L > 0 \tag{7.130}$$

And if that is true for a given value of L and λ, then clearly the following condition must be true as well:

$$\frac{\alpha+\beta}{\alpha\beta}\frac{4\bar{\theta}^2(1-\lambda)^2}{(4-\lambda)^4} - L > 0 \tag{7.131}$$

Thus, if the high quality product would be labeled in the single firm scenario it would also be labeled in the supply chain scenario.

Next, consider the condition necessary for the low quality firm to label in the single firm case:

$$\frac{1}{\alpha}\frac{\overline{\theta}^2\mu^3(4\mu-7)(4\mu^2-3\mu+2)}{4(4\mu-1)^6} - L > \frac{1}{\alpha}\frac{2\bar{\theta}^2\lambda(1-\lambda)^2}{(4-\lambda)^4} \tag{7.132}$$

Rewriting in terms of L we can see that:

$$\frac{1}{\alpha}\left(\frac{\overline{\theta}^2\mu^3(4\mu-7)(4\mu^2-3\mu+2)}{4(4\mu-1)^6} - \frac{2\bar{\theta}^2\lambda(1-\lambda)^2}{(4-\lambda)^4}\right) > L \tag{7.133}$$

If that condition is true, then it must also be true that:

$$\frac{\alpha+\beta}{\alpha\beta}\left(\frac{\overline{\theta}^2\mu^3(4\mu-7)(4\mu^2-3\mu+2)}{4(4\mu-1)^6} - \frac{2\bar{\theta}^2\lambda(1-\lambda)^2}{(4-\lambda)^4}\right) > L \tag{7.134}$$

And thus for any value of λ and L for which the low quality product is labeled in the single firm scenario it will also be labeled in the supply chain scenario. Taken together we have shown that given an equal or greater number of labeled products, the supply chain scenario produces higher social welfare, and that for any values of L and λ the supply chain scenario will result in at least as many products being labeled. Therefore, the supply chain scenario produces a higher social welfare than the single firm scenario. □

7.6.3.2 High Certification Costs

If the certification costs are instead very high compared to the cost of performing the measurement, then both the upstream supplier and downstream firm incur a labeling cost equal to the single firm case, and $L_u + L_d = 2L$. The conditions for the supply chain scenario to produce greater profits for the low quality supply chain when both products are labeled can then be written as:

$$\frac{1}{\beta}\frac{\overline{\theta}^2\mu^3(4\mu-7)(4\mu^2-3\mu+2)}{4(4\mu-1)^6} > L \tag{7.135}$$

And for the high quality supply chain as:

$$\frac{1}{\beta}\frac{4\bar{\theta}^2\mu^3(4\mu^2-3\mu+2)(4\mu-7)}{(4\mu-1)^6} > L \tag{7.136}$$

For the scenario where only one product is labeled profits will be higher for the low quality supply chain provided:

$$\frac{1}{\beta}\frac{2\bar{\theta}^2\lambda(1-\lambda)^2}{(4-\lambda)^4} > 0 \tag{7.137}$$

And for the high quality supply chain provided:

$$\frac{1}{\beta}\frac{4\bar{\theta}^2(1-\lambda)^2}{(4-\lambda)^4} > L \tag{7.138}$$

If the abatement costs are higher at the upstream firm, that is $\beta > \alpha$, then the upstream firm will only choose to label if the cost of the label is sufficiently low that the cost of obtaining the label is offset by the increase in profits. If this is not true, then either the downstream firm alone will label or the product will be unlabeled. If abatement costs are lower at the upstream firm then the upstream firm will always choose to label provided the downstream firm also chooses to label. Further, even if the downstream firm would not choose to label when acting alone it may now be profitable for both firms to label if the abatement costs are low enough at the upstream firm to enable the supply chain as a whole to generate a profit. The low quality firm always earns higher profits when it chooses not to label than in the single tier case, as the increased quality level of the labeling firm creates more differentiation and allows for a higher price. Assuming the conditions for the upstream firm to label are met then the resulting equilibrium results for the supply chain are shown in Table 7.10.

Proposition 7.6. *If the certification cost is high the inclusion of the upstream supplier increases social welfare provided abatement costs are not higher at the upstream supplier.*

Proof. Our proof here follows from Proposition 7.5, as the price, quality, and quantity results are identical to the case with low certification costs. Thus, the consumer surplus and societal benefit from emissions reductions will be higher in the supply chain scenario than the single firm scenario for an equal number of labeled products. Further, the producer surplus will

Label Cost (L)	Perceived Quality (λ)	Supply Chain 1 Decision	Supply Chain 1 Profit	Supply Chain 2 Decision	Supply Chain 2 Profit
$0 < L < .00076\bar{\theta}^2 \frac{\alpha+\beta}{\alpha\beta}$	$\lambda < \lambda_1^{'}$ or $\lambda > \lambda_2^{'}$	Label	$\frac{\alpha+\beta}{\alpha\beta} \frac{\bar{\theta}^2 \mu^3 (4\mu-7)(4\mu^2-3\mu+2)}{4(4\mu-1)^6} - 2L$	Label	$\frac{\alpha+\beta}{\alpha\beta} \frac{16\bar{\theta}^2 \mu^3 (4\mu^2-3\mu+2)(4\mu-7)}{4(4\mu-1)^6} - 2L$
$0 < L < .00076\bar{\theta}^2 \frac{\alpha+\beta}{\alpha\beta}$	$\lambda_1^{'} < \lambda < \lambda_2^{'}$	No Label	$\frac{\alpha+\beta}{\alpha\beta} \frac{2\bar{\theta}^2 \lambda(1-\lambda)^2}{(4-\lambda)^4}$	Label	$\frac{\alpha+\beta}{\alpha\beta} \frac{4\bar{\theta}^2 (1-\lambda)^2}{(4-\lambda)^4} - 2L$
$.00076\bar{\theta}^2 \frac{\alpha+\beta}{\alpha\beta} < L < \frac{\bar{\theta}^2}{64} \frac{\alpha+\beta}{\alpha\beta}$	$\lambda < \lambda_0^{'}$	No Label	$\frac{\alpha+\beta}{\alpha\beta} \frac{2\bar{\theta}^2 \lambda(1-\lambda)^2}{(4-\lambda)^4}$	Label	$\frac{\alpha+\beta}{\alpha\beta} \frac{4\bar{\theta}^2 (1-\lambda)^2}{(4-\lambda)^4} - 2L$
$.00076\bar{\theta}^2 \frac{\alpha+\beta}{\alpha\beta} < L < \frac{\theta^2}{64} \frac{\alpha+\beta}{\alpha\beta}$	$\lambda > \lambda_0^{'}$	No Label	0	No Label	0
$L > \frac{\theta^2}{64} \frac{\alpha+\beta}{\alpha\beta}$	any	No Label	0	No Label	0

Table 7.10: Equilibrium Results with High Certification Costs

also be higher, as when $\beta < \alpha$ the inclusion of the upstream firm always increases the profit of the supply chain.

Next, we consider the social welfare between the case where both products are labeled and where only one product is labeled. Following the same logic as in Proposition 7.2 we can see that the case with both products labeled has higher social welfare if:

$$2L < \frac{\alpha+\beta}{\alpha\beta}\bar{\theta}^2\left(.03459 - \frac{2\lambda^3 - 5\lambda^2 - 5\lambda + 8}{(4-\lambda)^4}\right) + \frac{\alpha+\beta}{\alpha\beta}\bar{\theta}\rho\left(.07282 - \frac{4\lambda^2 - 20\lambda + 16}{(4-\lambda)^4}\right) \tag{7.139}$$

The right hand side reaches a minimum of $.00334\frac{\alpha+\beta}{\alpha\beta}\bar{\theta}^2 + .01032\frac{\alpha+\beta}{\alpha\beta}\bar{\theta}\rho$ at $\lambda = 0$. For both products to be labeled we must have $L < .00076\bar{\theta}^2\frac{\alpha+\beta}{\alpha\beta}$, and thus the social welfare will be higher when both products are labeled as opposed to when only one product is labeled.

We have now shown that social welfare is higher in the supply chain scenario than the single firm scenario provided that an equal or greater number of products are labeled, and thus total social welfare will be higher provided the inclusion of the upstream supplier does not result in less products being labeled. First, by inspection the range of values of L for which products will be labeled is greater in the supply chain scenario than the single firm scenario. Next, at any given value of L and λ for which one or both products are labeled in the single firm scenario at least that many products are labeled in the supply chain scenario. Consider that if at a given value of L and λ only the one product is labeled in the single firm scenario, then we know that the high quality firm's profit must be positive. Therefore, the following condition is true:

$$\frac{1}{\alpha}\frac{4\bar{\theta}^2(1-\lambda)^2}{(4-\lambda)^4} - L > 0 \tag{7.140}$$

In order for the high quality supply chain to label at these values of L and λ then the following condition must be true:

$$\frac{\alpha+\beta}{\alpha\beta}\frac{4\bar{\theta}^2(1-\lambda)^2}{(4-\lambda)^4} - 2L > 0 \tag{7.141a}$$

Rewriting this expression we have:

$$\frac{\alpha+\beta}{\beta}\left(\frac{1}{\alpha}\frac{4\bar{\theta}^2(1-\lambda)^2}{(4-\lambda)^4}\right)-2L>0 \tag{7.141b}$$

From (7.140) we know that $\frac{1}{\alpha}\frac{4\bar{\theta}^2(1-\lambda)^2}{(4-\lambda)^4}>L$, which allows us to say:

$$\frac{\alpha+\beta}{\beta}\left(\frac{1}{\alpha}\frac{4\bar{\theta}^2(1-\lambda)^2}{(4-\lambda)^4}\right)-2L>\frac{\alpha+\beta}{\beta}\left(\frac{1}{\alpha}\frac{4\bar{\theta}^2(1-\lambda)^2}{(4-\lambda)^4}\right)-2\left(\frac{1}{\alpha}\frac{4\bar{\theta}^2(1-\lambda)^2}{(4-\lambda)^4}\right) \tag{7.142}$$

And given that the right hand side of this expression is greater than 0 when $\beta<\alpha$ we can see that for given values of L and λ the supply chain scenario will always result in the high quality product being labeled provided the single firm scenario did.

Next, consider the condition necessary for the low quality product to be labeled in the single firm case:

$$\frac{1}{\alpha}\frac{\overline{\theta}^2\mu^3(4\mu-7)(4\mu^2-3\mu+2)}{4(4\mu-1)^6}-L>\frac{1}{\alpha}\frac{2\bar{\theta}^2\lambda(1-\lambda)^2}{(4-\lambda)^4} \tag{7.143a}$$

Rewriting in terms of L we can see that:

$$\frac{1}{\alpha}\left(\frac{\overline{\theta}^2\mu^3(4\mu-7)(4\mu^2-3\mu+2)}{4(4\mu-1)^6}-\frac{2\bar{\theta}^2\lambda(1-\lambda)^2}{(4-\lambda)^4}\right)>L \tag{7.143b}$$

And the condition that the low quality product is labeled in the supply chain scenario requires:

$$\frac{\alpha+\beta}{\alpha\beta}\frac{\overline{\theta}^2\mu^3(4\mu-7)(4\mu^2-3\mu+2)}{4(4\mu-1)^6}-2L>\frac{\alpha+\beta}{\alpha\beta}\frac{2\bar{\theta}^2\lambda(1-\lambda)^2}{(4-\lambda)^4} \tag{7.144a}$$

Which can be rewritten as:

$$\frac{\alpha+\beta}{\alpha\beta}\left(\frac{\overline{\theta}^2\mu^3(4\mu-7)(4\mu^2-3\mu+2)}{4(4\mu-1)^6}-\frac{2\bar{\theta}^2\lambda(1-\lambda)^2}{(4-\lambda)^4}\right)>2L \tag{7.144b}$$

Finally, if (7.143b) is true, then (7.144b) is true for the case where $\beta<\alpha$, and thus for any value of λ and L for which the low quality product is labeled in the single firm scenario it will also be labeled in the supply chain scenario. Taken together we have shown that given an equal or greater number of labeled products the supply chain scenario produces higher social welfare, and that for any values of L and λ the supply chain scenario will result in at least as many products being labeled. Therefore, the supply chain scenario produces a higher social welfare than the single firm scenario even when certification costs are high, provided abatement costs are lower at the upstream firm. □

Proposition 7.7. *Inclusion of the upstream firm may reduce social welfare when the certification costs are high and abatement costs are higher at the upstream firm.*

Proof. For social welfare to decrease with the inclusion of the upstream firm it must be true that the number of labeled products decreases due to the upstream firm. We have already shown that this does not occur when abatement costs are lower at the upstream firm. However, when abatement costs are high this may be possible. First, consider the case where only the high quality product is labeled in the single firm case. Inclusion of the upstream firm in the supply chain scenario clearly can not cause the downstream firm to stop labeling, as if it was profitable to label without the upstream firm then it can continue to be profitable simply by purchasing an unlabeled zero quality product from the upstream supplier. Thus, it must be that inclusion of the upstream supplier may cause the low quality firm to decide not to label its product. For this to be the case the following conditions must be true:

- The profit for the low quality supply chain must be higher without labeling than the profit with labeling, either with or without inclusion of the upstream supplier.
- Abatement costs must be higher at the upstream firm.
- The cost of the label must be low enough that the low quality product is labeled in the single firm scenario, but not in the supply chain scenario.

The profit condition requires that:

$$\frac{\alpha+\beta}{\alpha\beta}\frac{2\bar{\theta}^2\lambda(1-\lambda)^2}{(4-\lambda)^4} > \frac{1}{\alpha}\frac{\overline{\theta}^2\mu^3(4\mu-7)(4\mu^2-3\mu+2)}{4(4\mu-1)^6} - L \tag{7.145}$$

and:
$$\frac{\alpha+\beta}{\alpha\beta}\frac{2\bar{\theta}^2\lambda(1-\lambda)^2}{(4-\lambda)^4} > \frac{\alpha+\beta}{\alpha\beta}\frac{\overline{\theta}^2\mu^3(4\mu-7)(4\mu^2-3\mu+2)}{4(4\mu-1)^6} - 2L \tag{7.146}$$

The condition that the low quality firm would be willing to label in the single firm scenario requires:
$$\frac{1}{\alpha}\frac{\overline{\theta}^2\mu^3(4\mu-7)(4\mu^2-3\mu+2)}{4(4\mu-1)^6} - L > 0 \tag{7.147}$$

If these conditions are met then the total social welfare without inclusion of the upstream firm is equal to the case where both firms choose to label, and is given by;

$$\frac{\bar{\theta}}{\alpha}\left(.03459\bar{\theta} + .07282\rho\right) - 2L \tag{7.148}$$

And inclusion of the upstream firm results in only the high quality product being labeled, giving a social welfare of:

$$\frac{\alpha+\beta}{\alpha\beta}\frac{\bar{\theta}^2\left(2\lambda^3-5\lambda^2-5\lambda+8\right)+4\rho\bar{\theta}\left(\lambda^2-5\lambda+4\right)}{(4-\lambda)^4} - 2L \tag{7.149}$$

A decrease in social welfare requires that:

$$\frac{\alpha+\beta}{\alpha\beta}\frac{\bar{\theta}^2\left(2\lambda^3-5\lambda^2-5\lambda+8\right)+4\rho\bar{\theta}\left(\lambda^2-5\lambda+4\right)}{(4-\lambda)^4} - 2L < \frac{\bar{\theta}}{\alpha}\left(.03459\bar{\theta} + .07282\rho\right) - 2L \tag{7.150a}$$

Rewriting gives this expression:

$$\frac{\bar{\theta}^2}{\alpha}\left(.03459 - \frac{\alpha+\beta}{\beta}\frac{\left(2\lambda^3-5\lambda^2-5\lambda+8\right)}{(4-\lambda)^4}\right) + \frac{\bar{\theta}\rho}{\alpha}\left(.07282 - \frac{\alpha+\beta}{\beta}\frac{4\rho\bar{\theta}\left(\lambda^2-5\lambda+4\right)}{(4-\lambda)^4}\right) > 0 \tag{7.150b}$$

If values exist such that (7.145), (7.146), (7.147), and (7.150b) are all true this will show the existence of a scenario where inclusion of the upstream supplier resulted in a decrease in social welfare.

If we set $\lambda = 0.5$, $\alpha = 0.5$, $\beta = 0.75$, $\rho = 0.5$, $\theta = 1$, and $L = 0.001$, the conditions for a decrease in social welfare are met. The low quality product is labeled in the single firm scenario; the high quality product is labeled in both the single firm and supply chain scenarios; the low quality product is not labeled in the supply chain scenario; and social welfare is lower under the supply chain scenario than the single firm scenario. Thus, it is possible that social welfare can be decreased when including the upstream firm, but only under certain conditions when certification costs are high and abatement costs are higher at the upstream firm. □

7.6.4 Discussion

In this section we presented an extension of the carbon label model that allows for the upstream supplier in the supply chain to contribute to reductions in the carbon footprint. Consistent with our carbon label framework from Chapter 5 we require the upstream firm to also invest in a label in order to communicate quality to the downstream firm. By including the efforts of the upstream supplier in the final product carbon label, the profits of the supply chain, the benefit to consumers, and the overall reduction in emissions can be increased. Our results show that the benefits are dependent on the relative costs of the label and the abatement cost structure at the upstream and downstream firms. Under a scenario where the cost of label certification is low, and cooperation between the upstream and downstream firms results in no net increase in labeling costs, social welfare is always improved. The firms choose higher levels of quality and price, which benefits both the firms and consumers. When certification costs are high, and the addition of a second label results in double the labeling costs, social welfare is improved provided abatement costs are lower at the upstream firm. When this is not the case it may result in a decrease in social welfare under certain conditions, as the low quality firm stands to gain more by forgoing a label.

7.7 Conclusions

In this chapter we developed a vertical differentiation model for a product carbon label. Our model departs from previous work by introducing a label that is both costly to obtain, voluntary, and capable of communicating a continuous level of product quality. In addition to the standard results showing the importance of consumer willingness to pay and the cost of implementing quality improvements, our model introduces two other key parameters, the cost of obtaining the label and the perceived quality of unlabeled products by the consumer.

Our results show that when the cost of the label is sufficiently low, both firms are able to earn profits above the undifferentiated case by investing in emissions reductions and obtaining a label for their products. The firm producing the good of lower quality may choose to forgo the label and earn greater profits if consumers perceive the quality of unlabeled products to be neither too poor nor too close in quality to a labeled product. As the cost of obtaining the label increases it may no longer be possible for one or both of the firms to profitably label their product. When firms choose not to label their product they also choose not to invest in reducing carbon emissions.

Our analysis of social welfare shows that the scenario where both products are labeled produces the most benefit to society. This suggests that the authority in charge of the label should focus on reducing the cost required to obtain the label in order to encourage more labeling. Under most conditions social welfare can also be improved by informing consumers regarding the benefits of labeled products, and thus reducing the perceived quality of unlabeled products. However, the best outcome involves both products being labeled, and this can only occur if the cost of the label is low enough, as under high label costs the firm producing the lower quality product will never be able to profitably label. The reduction in perceived quality of unlabeled products can either encourage the non-labeling firm to adopt a label, or else encourage the labeling firm to increase the quality of their product. The result of either outcome is an increase in social welfare. In one specific case, reducing the perceived quality of unlabeled products may reduce social welfare. This occurs if both products are currently labeled and the perceived quality of unlabeled products is very high. In this situation a reduction in the perceived quality of the unlabeled product could allow the producer of the lower quality product to stop labeling the product and earn higher profits.

In response to recent research showing that consumers may be confused by current carbon labels we also consider the case of a standard Type I certification style eco-label where a labeling authority establishes a minimum quality standard required to earn a carbon reduction label. Rather than communicate the exact carbon footprint of the product these labels provide a certification that the product meets some carbon reduction target. Our results show that the labeling authority can create greater social welfare with this style of label as long as their choice of minimum quality is not too costly to achieve. This is due to the ability of the labeling authority to consider the overall social welfare when designing the minimum quality standard. In labels that communicate the exact carbon footprint of the product, the firms decide their preferred quality level and make the choice based solely on their own profit maximization.

Finally, as the carbon footprint of a product is the result of the actions of the entire supply chain, we extend our label model to consider the inclusion of an upstream supplier in the carbon labeling process. The upstream firm also has the ability to impact the product's quality level through its own abatement efforts. The upstream firm must certify their results through a business-to-business style carbon label, and providing this carbon footprint information can potentially reduce the costs of obtaining a label to the downstream firm. When the cost of label certification is low in comparison to the cost of performing the label measurement this results in an increase in profits for the supply chain and an increase in overall social welfare. When the cost of certification is high the upstream firm will only choose to label if the increased profits can offset the cost of obtaining the label. If the cost of abatement is lower at the upstream firm this results in an increase in labeled products in some situations, but if costs are higher the low quality firm may forgo a label under certain conditions.

Our supply chain model focused on the vertically integrated supply chain in order to gain insight regarding optimal behavior of the supply chain as a whole. Inherent in our model is the assumption that reducing and reporting the carbon footprint of a product is a costly endeavor. In practice there may be many instances where reducing the carbon footprint of a product results in cost savings, such as through reduced fuel or electricity consumption. However, we choose to focus on the situation where improving quality is costly, as any carbon footprint reduction effort that also reduces cost should be implemented even with no consideration of the potential reductions in the carbon footprint. The question of interest here is whether firms will go to the effort to reduce and report their carbon footprint even when it is costly to do so, and in our model the incentive to do so comes from consumer willingness to pay a premium for lower carbon products.

Our results provide justification for why firms would voluntarily choose to disclose carbon footprint information to consumers and downstream partners in the supply chain. Consumers that are willing to pay for lower carbon products represent a source of increased revenue, but only when firms can communicate the carbon footprint of their products through a labeling mechanism. As the carbon footprint of the product is dependent on actions upstream in the supply chain, we show that even firms without direct sales to consumers can benefit the supply chain through their efforts at emissions reductions. However, consideration must be given as to how this will work in practice before drawing too strong of conclusions. If upstream suppliers embark on costly efforts to reduce and measure the carbon footprint of their product they will seek to recoup this costs through higher prices. Our results show that this can be optimal for the supply chain as a whole, but not to how the downstream firm balances paying higher prices to its suppliers with charging higher prices to consumers.

Chapter 8

Conclusions

In this thesis we set out to answer the question, "How do we measure the carbon efficiency of a supply chain?" We further broke this question down into three subquestions related to defining supply chain carbon efficiency, the methods used to measure it, and how it works in the context of a supply chain. In this chapter we identify the contributions made in this thesis by answering those questions and identify areas of future work.

8.1 Contributions

This thesis makes three primary contributions to the field. First, we created a definition of supply chain carbon efficiency and proposed an attributional approach to Life Cycle Assessment as the appropriate method for measuring it. Second, we presented a carbon label framework as a method for overcoming issues related to performing an LCA of an entire supply chain, and we showed how information sharing can be used in the supply chain to provide more accurate carbon footprint measurements. Third, we developed a model of product carbon labels to show why firms would be willing to voluntarily measure and share the carbon footprint of their products. These contributions are covered in more detail in the following sections.

8.1.1 Definition of Supply Chain Carbon Efficiency

In Chapter 2 we defined supply chain carbon efficiency as "the ratio of the supply chain output, measured by the total quantity of product produced, to the total greenhouse gas emissions attributable to the product produced by the entire supply chain, from the source of raw materials through product end-of-life". This definition builds upon the existing body of work in supply chain performance measurement and eco-efficiency to present a definition of a specific metric that encapsulates the relevant aspects of environmental performance and supply chain management.

The first key aspect of this definition is its application to the idea of the extended supply chain. The extended supply chain concept is common in the green supply chain management literature but neglected in traditional supply chain definitions that end at the consumer. Given the importance of product use and end-of-life issues in Life Cycle Assessment and the focus on closed and semi-closed loop supply chains in green supply chain management, the extended definition of the supply chain is necessary to fully capture the performance of the supply chain as a whole.

The second key aspect of our definition is defining efficiency in terms of the ratio between total output and greenhouse gas emissions. This draws from aspects of both supply chain performance measurement and the sustainability literature on eco-efficiency. Efficiency, along with effectiveness, is one of two aspects of performance measurement. It has been routinely identified as a key metric in the supply chain literature, though different definitions have been used. In viewing the supply chain as a transformative process that takes raw materials and turns them in to useful products, we draw upon the definition of transformational efficiency to define supply chain efficiency and combine this with the definition of eco-efficiency to develop our definition of supply chain carbon efficiency. Our definition is compatible across different organizations, as defined by the GRI's generally applicable indicators as well as the concept of environmental common denominators. This makes it suitable for use in the supply chain, where data must be collected across different processes and organizations in a way that can be combined to measure the performance as a whole.

Finally, our definition is also compatible with the concept of a product's life cycle used in LCA, and thus we identify LCA as the appropriate method for measuring supply chain carbon efficiency. LCA is the accepted method for measuring the carbon footprint of a product, defined as the total greenhouse gas emissions per unit of product. This measure is in fact the inverse of the carbon efficiency of the supply chain, and so the process of measuring the carbon footprint of a product serves as a way of measuring the carbon efficiency of the supply chain.

8.1.2 Carbon Label Framework

In Chapter 4 we demonstrated an example of using LCA to measure the carbon footprint of a product through a case study of the banana supply chain. In partnership with Chiquita and Shaw's we were able to collect primary data for a significant portion of the supply chain and develop an LCA model to estimate the carbon footprint of bananas sold in North America and Europe. Based on the results of this study and a review of sources of uncertainty in the LCA literature, we identified the lack of access to relevant data and variability in the supply chain as significant obstacles to the use of LCA to measure the carbon footprint of supply chains.

To overcome these obstacles we proposed a system of information sharing between supply chain partners to provide access to relevant data that is currently unavailable or too costly for firms to acquire. This builds on the history of information sharing in supply chains traditionally applied to demand and inventory problems. However, due to the credence nature of many environmental attributes, including the carbon footprint, we identify a possible violation of the incentive compatibility principle of good supply chain information sharing systems. With no method of verifying carbon footprint claims, firms may be reluctant to make decisions based on possibly untrustworthy claims. Through the framework of a carbon label we show how a third party can increase the trust in these claims by providing services such as standards setting and certification. Using this framework we define a carbon label in terms of the three dimensions of traceability: breadth, depth, and precision.

Though this framework is useful for solving issues of data availability in the Life Cycle Assessment process, it magnifies issues related to supply chain variability. If carbon footprint information supplied to customers is to be used in the procurement process, then accurately measuring the carbon footprint at an appropriate level of precision to support the decision becomes necessary. Through an analysis of the mode and carrier choice decision in transportation we show how the use of average performance measures can distort carbon footprint information and lead to poor decisions. Drawing on the concepts of management accounting we propose a system based on Activity Based Costing to enable firms to more accurately calculate the carbon footprint of individual customers and products. We demonstrate this in the mode selection decision through the use of the carbon market area concept in intermodal transportation and with an application to truckload procurement auctions in the carrier selection step. These improved metrics make use of information readily available to the carrier, but not to the shipper, to demonstrate how information sharing between supply chain partners can improve the carbon efficiency of the supply chain.

8.1.3 Vertical Differentiation Model of Product Carbon Labels

In Chapter 7 we presented a vertical differentiation model of product carbon labels. Our model builds on existing work in the area of eco-labels in a number of ways. First, our model considers a label that is both voluntary and continuous. Despite significant attention to Type I certification-style eco-labels, there has been relatively little research on Type III labels that communicate an exact level of quality. Our work also introduces two additional parameters, the cost of the label and the consumer perception of unlabeled products, that have significant impact on the final labeling decision. Our results show that reducing the cost of the label encourages more firms to label and creates an increase in social welfare. We also show that in most cases working to increase the effectiveness of labels by reducing public perception of the quality of unlabeled products also leads to an increase in social welfare, as the labeling firm produces at a higher quality level when it reaps the most benefit from its investment in quality.

In addition to this basic model of product carbon labels we consider two extensions. Owing to reports of consumer confusion by exact carbon footprint labels we model a product carbon label as a Type I certification-style label. Our results indicate that this type of label achieves a higher level of social welfare, as the labeling authority is able to set the minimum quality standard in a way that benefits society as a whole. This increase in social welfare comes at the expense of the labeling firm, which usually achieves lower profits than under a Type III label. In the second model extension we address the role of upstream firms in the supply chain in reducing product carbon footprints. We show that when certification costs are low the inclusion of the upstream firms leads to more labeling, higher profits for the supply chain, and an increase in social welfare. When certification costs are high the results depend on the relative cost of reducing emissions. If the upstream firm can reduce emissions at a lower cost than the downstream firm, the benefits to the supply chain hold.

8.1.4 Discussion

In summarizing these contributions we emphasize the need for collaboration in the supply chain to effectively measure and reduce carbon footprints, and highlight the role of third parties in effectively enabling this collaboration. The decentralized nature of supply chains means that individual firms often lack the resources or information to effectively measure the carbon footprint over the whole supply chain. In traditional supply chain management the profit motive can induce sharing and collaboration without the need for outside intervention. However, the credence nature of carbon emissions makes such an arrangement unlikely to occur in this case, as unverified environmental claims tend to be viewed as untrustworthy. We believe third parties have an important role to play by providing services such as standard setting and certification that establish the common language and trust necessary to effectively share carbon footprint information in the supply chain.

8.2 Limitations and Future Work

For each of the major contributions to this thesis we have identified limitations and areas for future work. First, our focus on carbon efficiency is limited in scope compared to the full range of supply chain and sustainability performance measurement. Second, our carbon label framework may not be appropriate for extension to all other environmental impacts. Third, our carbon label model focuses on the optimal actions of the supply chain as a whole, but does not address the dynamics between the upstream and downstream firm in the supply chain. In the following sections we discuss these limitations and identify areas for future work.

8.2.1 Moving Beyond Carbon Efficiency

In Chapter 2 we reviewed the literature on supply chain performance measurement and noted the existence of many different kinds of metrics, of which carbon efficiency is only one. We note that a focus on carbon efficiency presents only a limited picture regarding the performance of the supply chain as a whole. Efficiency represents one goal, but a performance measurement system must consider effectiveness as well. To fully capture the performance of the supply chain with respect to greenhouse gas emissions, some measure of effectiveness, such as total emissions, should be included to balance the relative performance measured by efficiency. The literature on eco-efficiency has pointed out the limitations of efficiency as a single metric in sustainability, and this discussion should be considered in implementing sustainability metrics for the supply chain.

Carbon efficiency represents a limited metric not just due to the focus on efficiency, but also due to the focus on only environmental and economic factors. The field of supply chain management has developed a number of other categories of metrics and measures, including time, flexibility, and cost. Integrating metrics of all different types into a single performance measurement system remains a challenge, and carbon efficiency only illustrates one particular dimension of performance. In addition to other types of measures of supply chain performance, our definition of carbon efficiency is limited from a sustainability perspective as well. Eco-efficiency measures only capture two of the three dimensions of sustainability. This neglects the social dimensions of sustainability, such as ethical treatment of employees and benefits to communities surrounding the company's operations.

We identify at least three areas where future work can build on our contribution of carbon efficiency as a supply chain metric to construct an overall performance measurement system:

1. By developing a metric that captures carbon effectiveness, the other relevant dimensions to greenhouse gas emissions performance in the supply chain.

2. By developing a framework for integrating carbon efficiency with other types of per-

formance metrics to capture the overall performance of a supply chain.

3. By developing complete sustainability metrics that include the social dimension of sustainability neglected by eco-efficiency metrics.

8.2.2 Application to Other Environmental Impacts

Our focus on carbon efficiency was driven primarily by the recognition of climate change as one of the most pressing environmental issues we are currently facing. However, it is not the only environmental issue, and in particular cases it may not be the most important. Much of the work in our proposed framework for sharing information in the supply chain and modeling the role of carbon labels in driving emissions reductions assumes an additive nature of the the carbon footprint. That is, at each stage in the supply chain, the carbon emissions from upstream can be added to the emissions at the current stage to incrementally measure the total supply chain carbon footprint. This additive nature was explicitly captured in our extended version of the two-stage product carbon label. This feature holds for greenhouse gas emissions where the environmental damage is usually considered independent of where the emissions occur, but may not hold for other environmental impacts. Consider the case of air pollution, another common environmental issue associated with transportation. The damage from pollution can be significantly different if the emissions occur in a densely populated area, and thus similar amounts of total pollution could produce significantly different amounts of damage. This scenario implies that the additive nature of the carbon footprint would not necessarily hold for a measure of air pollution.

With this in mind we propose that a second area of future work is identifying other important areas of environmental impact where a similar relationship to greenhouse gas emissions exists. These areas of environmental impact would be possible candidates for developing metrics that operate in a similar way to our proposed carbon efficiency metric. For environmental impacts that do not behave in this manner it will be necessary to identify the characteristics that differ in order to modify the current framework or even introduce an entirely new framework. Though a number of eco-labels exist in practice for a wide variety of environmental impacts, the labeling framework may not be applicable to the supply chain for all of them.

8.2.3 Extensions to the Carbon Label Model

In Chapter 7 we introduced a vertical differentiation model of product carbon labels and considered two extensions to the basic model. Though there are any number of different choices that could be made regarding the structure of the model, we want to highlight a particular issue of relevance to supply chain management. In extending the model to a two-tier supply chain we showed the effects of the upstream firm on the resulting product quality, firm profits, and social welfare. However, we did not cover in detail the many different relationships between the upstream and downstream firms in the supply chain and the resulting effects of changes in those structure. In particular we did not consider scenarios where the firms are decentralized and make their decisions based on maximizing their own profits rather than the supply chain as a whole. There is a rich history of studying the contractual arrangements between firms in supply chain management in an effort to identify how those arrangements affect individual and supply chain performance. We identify three areas where the relationships between the firms could be handled in an extended version of our supply chain model.

First, there is the issue of which firm acts first. In our model both firms are assumed to begin with a zero quality product and must invest in technology to improve quality. In the vertically integrated scenario the firms' choices of quality are solved simultaneously to find the supply chain optimal quality levels. In practice, however, one of the firms must act first. Either the upstream firm invests in a level of quality and offers a contract to the downstream firm at a given price and specified level of quality, or the downstream firm proposes a contract to the upstream firm specifying the price and level of quality. In either case the firm acting first seeks to choose the price and quality that maximize its own profits subject to the constraint that the other firm is willing to accept the contract.

Second, there is the issue of the level of information each firm has about the other. If the firm offering the contract does not know the cost function of the other firm this represents an area of asymmetric information. The firm offering the contract may be at a disadvantage due to this lack of information. This may have special relevance for the situation where the upstream firm offers the contract, as the downstream firm also has the ability to set the final price in the market place. The decision on how to handle public and private information could therefore have a significant impact on the final contract structure and outcome.

Finally, the structure of the contract itself can have an impact on the firm profits and the ability of the supply chain to achieve optimal price and quality levels. Even in simple models such as the newsvendor problem there is a rich base of literature regarding the structure of the contract between the upstream and downstream firms. By choosing different contracts the firms may induce the channel coordinating behavior and alter the distribution of profits between the firms. Given that our simple two-stage model shows the optimal supply chain choices and profits, finding a contract that can induce that channel coordinating behavior is a natural extension.

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