Production, Storage, and Distribution of Food: A Greenhouse Gas Life Cycle Assessment.

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ABSTRACT

Quantifying the greenhouse gas emissions associated with the various steps in the life cycle of food is important for understanding its relative contribution to global warming. The distance between the place of production and retail location, food-miles, is a main point of focus for advocates of reducing greenhouse gas emissions. Food-miles is not an adequate metric however for determining the environmental impact of food, as it does not take into account production, storage, and distribution differences.

In this paper, various life cycle analyses indicate that the methods used to produce food such as greenhouses and organic agriculture, in addition to where the food is produced, will be more significant in terms of greenhouse gas contribution than food-miles alone. The use of transportation distance as the only metric to evaluate the carbon footprint of food is too simplistic as the methods used to store food, the amount of food processing that is needed, and the type and amount of food packaging used will also affect the amount of emissions involved in the life cycles of food.

A total life cycle analyses is recommended in order to yield the most accurate results regarding the total carbon footprint of food. Consideration of the food supply chain structure, the scale of food distribution, and modes of transportation used are major factors in determining the size of the carbon footprint from food and are overlooked using the food-miles analysis.

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1. INTRODUCTION

1.1

Proponents of the localization of the food system argue that reducing the distance that food travels during its life cycle will help curb greenhouse gas emissions (Thompson *et al.*, 2008; Anderson, 2007). Prior to industrialized production and processing, most edible products typically travelled less than a day to the market, but new preservation and processing practices prolong freshness and allow for further sourcing of foodstuffs (Giovannucci *et al.*, 2010). Although the impact of transportation distance is important, full life cycle analyses indicate that for most foods transportation does not have the largest environmental impact.

Food-miles is the distance that food is transported from place of production to final retail location (Martinez *et al.*, 2010). The food-miles analysis however is not inclusive of all externalities such as production, storage, and distribution differences. The intent of this thesis is not to say that eating local food is bad for the environment. There are certainly benefits of eating locally such as stimulating local economies, supporting farmers, and fresher foods. The purpose of this paper however is to show that reducing the distance food travels is not justification enough to buy local food since food miles is not inclusive of other factors involved in the life cycle of food that effect life cycle emissions. There are typically too many variables to accurately make the conclusion that there is a correlation between a food having greater food miles and being worse for the environment, or vice versa. The greenhouse gas emissions involved in this life cycle can be affected by everything from economies of scale to the standardization of a shipping and transportation fleet. Owing to differences and variability in production, storage, and distribution of food, I believe that food miles alone is not a sufficient metric to use in determining the greenhouse gas emissions from food. Instead, I propose that life cycle assessments be used as an alternative to food miles to evaluate the environmental impacts of food.

This paper will assess the contributions made by different stages involved in the life cycle of food. This thesis: (1) Considers and compares how differences in production affect emissions, including protected cultivation; (2) Compares the CO_{2eq} emissions from organic versus conventional agricultural methodologies; (3) Discusses how regional differences such as climatic, environmental, and energy sourcing variability affect total CO_{2eq} involved in the lifecycle of food; (4) Examines the storage stages involved, touching on factors of storage methods and length of storage; (5) Discusses supply chain structures and logistical differences between large-scale and small-scale operations and how their respective CO_{2eq} emissions vary; (6) Addresses different methods of food distribution, such as food home delivery, and modes of transportation, including airfreight, shipping, trucks and cars, and how they differ in terms of their relative CO_{2eq} emissions.

One reason that food miles alone is an unreliable indicator of environmental impact is due to the fact that supply and production chains are seldom identical enough that one can judge the greenhouse gas emissions using a single metric. Figure 1 and Figure 2 are both product supply chains, but vary significantly in the number of intermediate steps between the supplier and consumer. Supply and production chains differ frequently in the number of marketing stages, transport modes used and types of fuel, frequency of trips, and even in how large or full the load sizes are. All of these factors can combine to make deducing a linear relationship between the distance of food transportation and environmental impact in terms greenhouse gas emissions nearly impossible.

Figure 1. A simple product supply chain. Source: (Wakeland *et al.*, 2011).

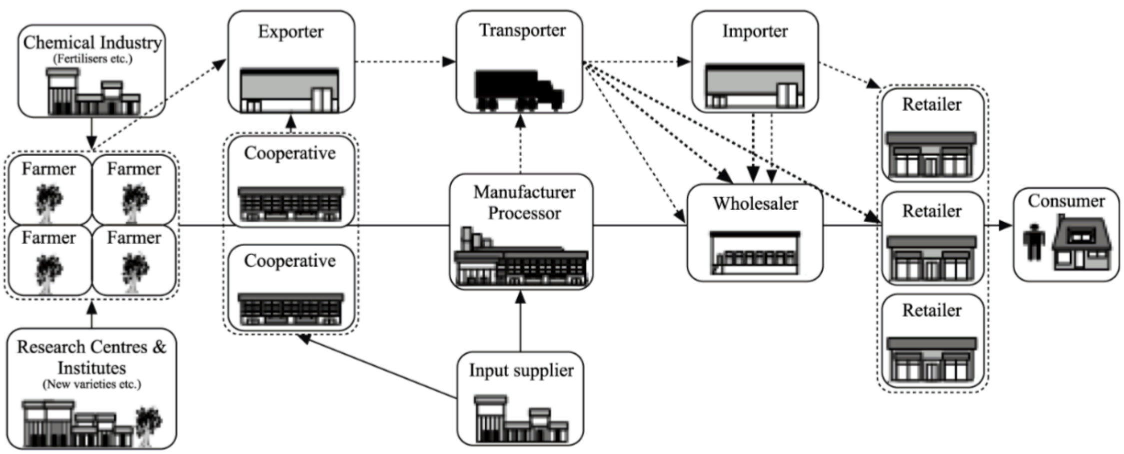

Figure 2. Food supply chain. Source: (Matopoulos *et al.*, 2007)

Owing to supply chain variability, a life cycle assessment is a practical tool for evaluating the environmental impacts of an individual food product within a defined system boundary. Life cycle assessment methods analyze the emissions and energy use of an entire supply chain, in addition to the problems associated with material and energy inputs to production systems (Brodt *et al.*, 2013). In this paper, life cycle assessments consider emissions from direct input activities, such as production and transport, and indirect emissions additions such as those generated by the manufacture of fertilizer, pesticides, and electricity. Incorporation of all associated emissions allows for a comprehensive analysis of the contributions from different stages involved in the life cycle of food (Edwards-Jones *et al.*, 2008).

The scale of the study will affect the life cycle assessment such that an analysis at the farm level, within a country, or between seasons for example will yield different results for the same product. Therefore, the most accurate assessments of the greenhouse gas emissions are obtained when the system boundaries of the life cycle assessment include all phases of the food chain (Edwards-Jones *et al.*, 2008). A full life cycle assessment could extend beyond national boundaries and continue through the consumption of final market goods to include the disposal of food waste (Canning *et al.*, 2010). Life cycle assessments are a helpful tool to get an encompassing view of the environmental impact differences between contrasting production, storage, and distribution methods. Food-miles is known to be an important aspect in the life cycle of food; the way in which food is produced, stored, and distributed also contribute to carbon dioxide equivalent emissions (CO_{2eq}). The fact that a life cycle assessment is a comprehensive approach will allow for the comparison of the emissions impact of transportation distance to other processes involved in the life cycle of food (Park *et al.*, 2016).

1.2 What are Greenhouse Gases?

Greenhouse gases are typically considered using the metric carbon dioxide equivalent emissions (CO_{2eq}). Carbon dioxide equivalent emissions are helpful as they indicate the concentration of carbon dioxide that would cause the same amount of radiative forcing as a given mixture of carbon dioxide and other greenhouse gases, all multiplied by their respective global warming potential (GWP) to take into account their differing residence times in the atmosphere (IPCC, 2007). Global warming potential is an index that describes the radiative characteristics of well-mixed greenhouse gases, and takes into account the effect of the differing times that these gases remain in the atmosphere and their relative ability to absorb outgoing infrared radiation. This is a useful index as it approximates the warming effect of a given greenhouse gas in today's atmosphere, relative to that of CO_2 (IPCC, 2007). For example, 1 kg of methane (CH_4) is equivalent to 25 kg of carbon dioxide (CO_2), and 1 kg of nitrous oxide (N_2O) is equivalent to 298 kg CO_2 over a 100-year time scale.

The term carbon footprint is defined as the total amount of greenhouse gases emitted by all steps involved in the life cycle of a product (Edwards-Jones *et al.*, 2008). As defined by the IPCC (Appendix I, 2007), greenhouses gases (GHGs) are atmospheric gases that absorb radiation at wavelengths within the spectrum of infrared radiation that is emitted by the surface of the Earth, the atmosphere, and the clouds. The absorption and emission of radiation by greenhouse gases drives the greenhouse effect, which leads to global warming.

The comparison of the CO_{2eq} emissions from different stages involved in the life cycle is warranted, as the amount of greenhouse gas emissions resulting from food is significant. For example, between ten and twelve percent of the total global anthropogenic CO_{2eq} emissions in 2005 were from agricultural sources, which amounts to 5.1 to 6.1 Gt of CO_{2eq} per year (IPCC, 2007). Greenhouse gases cause climate change, which can amplify extreme weather events such as droughts, heat waves and storms, and sea level rise (Smith and Olesen, 2010). This is important as extreme weather events associated with climate change are expected to affect global food production as future scenarios of increased temperatures will potentially reduce crop yields while encouraging weed and pest proliferation. Furthermore, projected changes in precipitation patterns could increase the occurrence of crop failures and lead to production declines in the long-term (Smith and Gregory, 2013). As such, there is a critical need to identify the greenhouse gas contributions from various stages involved in the life cycle of food in order to see where our CO_{2eq} mitigation efforts will be best spent in the future. Owing to the encompassing nature of life cycle assessments, they can be helpful for identifying alternatives for reducing greenhouse gas emissions of agriculture and food products at various life cycle stages.

2. FOOD PRODUCTION

2.1 Protected Cultivation- Greenhouses

When evaluating the CO_{2eq} emissions involved in the life cycle of food products, it is important to discuss how differences in production can affect emissions. Greenhouses and other forms of protected cultivation are an option for producing food in locations where the climate is less than ideal for outdoor growth. Heating greenhouses for the local production of food is energy intensive and can create greater CO_{2eq} emissions than those resulting from transporting food from sunnier climates where the food can grow outside without the external inputs to modify the climate. Growing food in more favorable agricultural conditions can also require fewer inputs in terms of fertilizers, pesticides, and energy, which can tip the CO_{2eq} emissions scale to favor the import of food products (Garnett, 2006). Producing foods in locations where climate, soil, and precipitation patterns are more conducive to food growth will require less external inputs of energy and resources making production more efficient in terms of CO_{2eq} emissions.

The way in which food is grown will make a difference in the energy used and greenhouse gas emissions involved in production. In essence, variations in the degree of the environmental impact of foods will arise through the methods of production. The use of greenhouses is an innovative solution to providing fresh year-round produce in places where the climate may not be suited to do so otherwise. In some cases the CO_{2eq} emissions from greenhouse food production are still less than those from transportation, justifying overseas sourcing (Watkiss *et al.*, 2006; Wright and Cowell, 2002**)**. However for the majority of cases, in food production systems that require protection, heating, and a controlled (modified) climate such as with greenhouses, the production stage will use more energy during cultivation than transportation, which can negate the energy and greenhouse gas emissions saved through sourcing food locally (Garnett, 2006). Local foods grown in greenhouses do not always yield the least emissions, nor do they always use less energy, which can justify the sourcing of distantly grown products. In a paper analyzing the differences between Swedish greenhouse produced tomatoes and open grown Southern European tomatoes for example, it was shown that the greenhouse tomatoes required far more energy per kg of tomatoes (66 MJ/kg), than did the open grown tomatoes (5.4 MJ/kg) (Carlsson-Kanyama *et al.*, 2003**).**

This previous example only considers the energy involved in the cultivation of the tomatoes, but studies such as Carlsson (1997) have also included the energy consumption involved in the production and transportation of the tomatoes. Carlsson (1997) looks at the cultivation and distribution of both nationally sourced and imported tomatoes to retail outlets in Sweden. To produce the tomatoes nationally in Sweden, greenhouses were used and the energy consumption involved in tomato production was 58.3 MJ/kg of tomatoes. The energy consumption involved in producing tomatoes in Spain without a greenhouse, was much less intensive at 1.5 MJ/kg of tomatoes (Carlsson, 1997). From a production standpoint, the unprotected outdoors cultivation without greenhouses is still much more energy conservative than the use of greenhouses.

Carlsson (1997) also considers the energy used in transporting tomatoes from Spain to Sweden to evaluate whether or not the sourcing of locally grown tomatoes is more environmentally friendly than the importation of tomatoes from Spain. An important factor affecting the energy used in the distribution of tomatoes from Spain to Sweden was the transportation mode that was chosen. Shipping with a boat from Spain to Sweden only consumed 2.2 MJ/kg of tomatoes, while transport via trucks consumed 3.9 MJ/kg of tomatoes. Airfreight consumed much more energy, totaling 50 MJ/kg of tomatoes. However, even when factoring in both the energy used in the production and transportation of tomatoes, the sourcing of tomatoes from Spain was less energy intensive than was the sourcing of locally grown greenhouse tomatoes. The total energy costs for tomatoes transported by ships, trucks, and planes was 3.7 MJ/kg, 4.6 MJ/kg, and 51.5 MJ/kg respectively. Comparing these values to the energy consumption involved in greenhouses in Sweden, 58.3 MJ/kg, the import of tomatoes is more energy conservative than sourcing from within Sweden, especially considering that this 58.3 MJ/kg is solely from tomato production and cultivation (Carlsson, 1997). In this case, sourcing locally is not a CO_{2eq} emissions conservative alternative with regards to importing tomatoes, due to the higher energy costs for greenhouse tomato production.

Milá *et al.* (2008) studied a similar greenhouse agricultural case comparing the associated CO_{2eq} emissions from protected horticulture of lettuce within Europe to those resulting from lettuce grown locally in greenhouses in Britain. The lettuce produced within British greenhouses was worse in terms of global warming potential and primary energy use, than was the imported lettuce grown in Europe (Milá *et al.*, 2008). Primary energy is the energy contained in raw fuels before any transformation to secondary or tertiary forms of energy (for example, coal (primary energy) is used to generate electricity (secondary energy)). This case illustrates that importing the openly grown lettuce is less energy intensive than the sourcing of local greenhouse lettuce. However, if the alternative to the British greenhouse lettuce was lettuce air-freighted from Africa, the greenhouse lettuce is likely better due to the impacts from jet fuel production and combustion involved in Ugandan lettuce due to airfreight (Milá *et al.*, 2008). The energy use of greenhouses is primarily due to the electricity needed to heat and to light the greenhouses (Jones, 2002). Therefore, using renewable energy technologies to heat and light greenhouses could be a worthwhile investment to improving the energy efficiencies of greenhouse crop production.

2.2 Organic Versus Conventional Agriculture

Organic food production is often cited as an environmentally friendly alternative to conventional agriculture because the ban on pesticides and synthetic fertilizer use drastically reduces the CO_{2eq} emissions involved in the production of food (Gomiero *et* *al.*, 2008). The use of synthetic fertilizers in conventional agriculture contributes significantly to the total CO_{2eq} emissions, between 0.3 and 0.6 Pg CO_{2eq} per year, or 0.6 to 1.2% of the world's total greenhouse gases, owing to the fact that production of fertilizers is energy intensive (See table 2) (Bellarby *et al.*, 2008). The increase of nitrogen fertilizer use and livestock production has caused global agricultural CH_4 and N_2O emissions to climb by 17% between 1990 and 2005. It is important to note that more energy conservative agricultural practices are needed as these emissions are projected to increase by another 35-60% by the year 2030 (FAO, 2002). Similarly, the U.S. EPA estimated that N_2O emissions will experience an increase of about 50% by 2020 (relative to 1990) (US-EPA, 2006). Organic farming is a viable solution to reducing CO_{2eq} emissions from the production of food as it can result in lower energy consumption per unit of land and per yield from 10% to 70% and 15% to 45%, respectively (Gomiero *et al.*, 2008).

Study	CO_2 emission (kg CO_2 /ha)			CO_2 emission per production unit (kg CO_2/t)		
	Conv.	Organic	Org. as % of conv.	Conv.	Organic	Org. as % of conv.
Winter wheat						
Rogasik *et al.* (1996)	826	443	−46	190	230	+21
Haas/Köpke (1994)	928	445	−57	149	110	−21
Reitmayr (1995)	1001[if]	429	−57	145[if]	100	−21
Potatoes						
Rogasik *et al.* (1996)	1661	1452	−13	46	62	+35
Haas & Köpke 1994)	1437	965	−33	46	48	0
Reitmayr (1995)	1153[if]	958	−17	30[if]	45	+50
Milk						
Lundström (1997)	—	—	—	203	212	+4
Haas *et al.* (2001)*	9400	6300	−67	1280[a]	428[a]	+65%
Haas *et al.* (2001)*				1300[b]	1300[b]	0
Crop management rotation						
Haas and Köpke (1994) in Stölze *et al.* (2000)*	1250	500	−40%	—	—	—
SRU (1996) in Stölze *et al.* (2000)*	1750	600	−34%	—	—	
Rogasik *et al.* (1996) in Stölze *et al.* (2000)*	730	380	−52%	—	—	—

Table 1. Table of CO_2 emissions of organic versus conventional methods for some productions. Source: (Gomiero *et al.*, 2008).

Component	**Energy Use (MJ/kg)**	**Emission Rate (kg CO_2/MJ)**
N	65	0.05
P	15	0.06
K	10	0.06
S	5	0.06
Lime	0.6	0.72

Table 2. Table of energy requirement (MJ/kg) to manufacture fertilizer components and the associated CO_2 emissions. Source: (Wells, 2001).

Organic agriculture can also help curb CO_{2eq} emissions associated with agriculture as it increases the potential soil carbon sinks in soil organic matter and aboveground biomass. Organic agricultural methods such as crop rotations with cover crops, green manures to increase biomass, agroforestry, and conservation-tillage systems all help to increase the amount of organic matter in the soil, thus reducing the amount of greenhouse gas emissions. Consequently, because soils managed using organic agriculture have a higher water holding capacity than soils from conventional agriculture,

CO_{2eq} emissions are further diminished due to less need for mechanical power to pump water for irrigation (Pretty *et al.*, 2002; Hansson *et al.*, 2007). Organic agriculture is not only beneficial for reducing CO_{2eq} emissions, but is also a solution to water shortage problems, especially in developing countries due to a projected increase in climate change-induced droughts (Gomiero *et al.*, 2008).

2.3 Regional Variations and Differences

The intensity of energy inputs used in food production and the associated CO_{2eq} emissions varies widely between regions due to climatic and environmental differences. It is imperative not to assume that food products can be produced in an equally energy efficient manner in all countries or provinces. There are natural regional variations and differences such as temperature, precipitation, and soil type, which can affect the total CO_{2eq} from food production. There are also anthropogenic regional differences such as the source from which a country derives its electricity (Table 3), which affects the total amount of CO_{2eq} emissions associated with the life cycle of food. These regional differences are typically overlooked when using food miles, and a comprehensive life cycle assessment allows for the total CO_{2eq} emissions that result from regional differences. Ensuring that regions are not treated equally is important as geographic differences can affect precipitation, the length of the growing season, soil types, and temperature, all factors that can play into regional CO_{2eq} emissions intensities associated with food.

Country of Consumption Origin	Emission, g per MJ Generated 1992	
	CO_2	CH_4
Denmark	313	-
Netherlands	204	-
Germany	218	-
Great Britain	199	-
Italy	178	$1.27*10^{-5}$
Spain	147	$1.06*10^{-5}$
Sweden	19	$3.45*10^{-5}$
"Other Countries"	$313 * 10^{157}$	-

Table 3: CO_2 and CH_4 emissions from electricity generation in the countries of consumption origin. Source: (Carlsson, 1997).

Depending on the country of the origin of food, there is a difference in the environmental impacts associated with the life cycle of food. For example, when comparing locally sourced food within the United Kingdom versus food sourced from Guatemala or Kenya, the energy consumption and greenhouse gas emissions associated with the food production within the United Kingdom is much greater than that from Guatemala or Kenya. This can be attributed to the fact that the use of renewable fuels in the United Kingdom only constitutes 3% of the total energy used, compared to Guatemala and Kenya, which respectively use 40% and 65% renewable fuel sources (Sim *et al.*, 2007).

The idea that the substitution of local for imported foods will reduce direct and indirect greenhouse gas emissions not always valid. A study by Avetisyan *et al.* (2014) portrays this in scenarios wherein the consumption of imported livestock is shifted to the consumption of domestic livestock in wealthy countries. In this instance there was a direct reduction in greenhouse gas emissions associated with international trade and transport. However, the reduction in transport emissions was overshadowed by the changes in global emissions resulting from differences in the emissions intensities of livestock production. It was subsequently found that replacing imported goods with local goods reduces global emissions only when done so in regions with relatively low emissions intensities, portraying the importance of looking at factors other than distance when determining the environmental impacts associated with food (Avetisyan *et al.*, 2014).

As portrayed in the previous example, regional emissions intensities are not all equivalent and these differences can discount the accuracy food miles arguments. To further this point, consider the fact that Canada typically imports its ruminant meat from the United States. Canada has a lower than average emissions intensity in meat production, but the United States has an even lower intensity. In this instance, replacing the import of United States meat products with local Canadian products would result in higher production-based emissions even when factoring in the emissions from transportation to Canada (Avetisyan *et al.*, 2014). This example displays how in this instance, the use of food miles alone to evaluate the contribution of transportation distance to life cycle emissions fails to take into account emissions differences at the regional level. Table 4 shows that in the majority of cases, whenever the domestic emissions intensity dominates the import-weighted intensity for a given region, the global emissions rise under a food-miles scenario. Table 5 on the other hand serves to display the heterogeneity of the relative impacts of the steps involved in the life cycle of food as it shows that in the cases where production is less emission intensive than transportation, the food miles story is supported by transport distance (Avetisyan *et al.* 2014).

Region with "food miles" experiment	Change in world emissions, MTCO2e			Ruminant meat emissions intensity, MkgCO2e/$	Ruminant meat import-weighted emissions intensity, MkgCO2e /$
	Ruminant meat	Transport	Total		
Japan	−78,029	−1,730	−37,746	1.47	12.69
Rest of European Countries	−40,171	−1,835	−37,661	3.91	10.12
United States	−130,113	−713	−114,601	4.45	8.07
Other East Europe	−82,509	−17,785	−148,750	4.95	8.27
East Asia	−41,167	−6,092	1,457	5.15	14.03
Middle Eastern and North Africa	−273,353	−14,264	−305,239	5.28	8.77
European Union	−82,642	−2,070	−84,503	5.74	8.11
Canada	20,089	−6,326	16,603	6.06	5.05
Russia	110,143	−9,818	103,699	10.44	7.58
Oceania countries	20,935	−2,657	10,771	11.42	10.62
Central and Caribbean Americas	−5,696	−2,928	−19,231	12.75	7.63
South and Other Americas	−151,646	−6,230	−159,103	17.91	19.37
China and Hong Kong	341,032	−5,451	302,773	24.63	11.84
Sub Saharan Africa	610,098	−4,838	599,864	41.82	37.00
Malaysia and Indonesia	245,830	−4,676	214,119	49.72	13.30
Brazil	813,044	−447	821,779	54.05	15.31
World	–	–	–	14.25	–

Table 4. Change in total emissions under a "food miles" scenario. (Avetisyan *et al.*, 2014).

Region with "food miles" experiment	Food product in "food miles" experiment[a]			
	Dairy products	Non-ruminant products	Vegetable and oil products	Processed rice products
United States	–	–	–	–
European Union	0.51	0.09	–	0.10
Brazil	0.17	–	–	0.11
Canada	0.71	0.88	–	–
Japan	0.04	0.00	–	0.00
China and Hong Kong	0.08	–	–	0.41
India	–	0.14	–	–
Central and Caribbean Americas	0.46	0.09	–	0.19
South and Other Americas	–	0.06	–	0.58
East Asia	0.12	–	–	–
Malaysia and Indonesia	0.03	–	–	–
Rest of South East Asia	0.42	–	–	–
Rest of South Asia	–	–	–	–
Russia	–	0.11	0.64	–
Other East Europe	0.16	0.12	0.69	–
Rest of European Countries	0.43	0.07	–	–
Middle Eastern and North Africa	0.34	–	0.51	0.11
Sub Saharan Africa	–	–	–	–
Oceania countries	–	–	0.06	–

Table 5. Share of global emissions change accounted for by transport related emissions. Source: (Avetisyan *et al.*, 2014).

As stated previously, the way in which energy is produced can also vary by region and is therefore an important factor to consider as some sources of energy will have greater CO_{2eq} emissions than others. When examining emissions released for roses grown in Kenya and sent to the Netherlands, the total emissions associated with this process are less than they would be if the roses were grown within the Netherlands. This is due to fact that Kenya uses renewable geothermal energy while the Netherlands uses fossil fuels for electricity (Williams, 2007). The food miles argument overlooks the important differences in regional energy sourcing even though it is an influential contribution to the total energy used and greenhouse gas emissions. The types of energy used to produce food and agricultural products will make a significant impact on the life cycle emissions intensities and is only accounted for through the use of a comprehensive life cycle assessment.

Additional region-specific variables such as climate, soil type, and availability of water are important to consider when evaluating CO_{2eq} emissions since they play substantial roles in determining the types of external inputs that are required and their associated environmental impacts, in addition to the overall production efficiency (Brodt *et al.*, 2013). Agricultural constraints are typically compensated for through the addition of external inputs, which can cause additional environmental impacts. Brodt *et al.* (2013) show how distance alone is not a valid indicator of environmental impact, and how regional differences should be considered.

Brodt *et al.* (2013) performed a life cycle assessment in order to quantify and compare the greenhouse gas emissions and energy use of tomato products grown, processed, and consumed within the Great Lakes region of the United States, to those produced in California and then shipped to the Great Lakes region. From a food miles perspective, it is expected that the products shipped from California would be much worse in terms of greenhouse gas emissions and energy use, owing to their comparatively long transport distance. However, the total energy use and greenhouse gas emissions is similar for the California products sold in the Great Lakes region and Great Lakes tomato products, even with the addition of bulk packaging and long-distance transport to Michigan.

The similarity in emissions and energy use is due to key regional biophysical variables in California. In terms of the production of tomatoes, California uses about 78% of the energy and only emits 67% of the greenhouse gases per kg of final product than Michigan. This is due to the fact that California soils are better suited for growing tomatoes since they do not need to have lime added to them to produce tomatoes properly. As Table 6 displays, the Michigan soils need an application of 510 kg of lime per hectare (Brodt *et al.*, 2013). The greenhouse gas emissions from the production of lime contribute 0.72 kg CO_{2eq} per MJ (Table 7) (Wells, 2001). Based on the application per hectare, the production of lime for this system would emit an additional 220.32 kg CO_{2eq} per hectare, compared to the lack thereof within the California agricultural system.

Key system inventory characteristics	Production system		
	California conventional	Michigan conventional	California organic
Yield (mt/ha)[a]	90	74	85
Soil amendments			
N (kg/ha)	197	137	16 mts/ha composted manure, 14 mts/ha fresh manure, 4 kg/ha fish powder, 1 kg/ha kelp (approx. 224 kg/ha N)
P_2O_5 (kg/ha)	62	155	–
K_2O (kg/ha)	1	410	–
Zinc chelate (l/ha)	2	–	–
Gypsum (mt/ha)	1.5	–	1.3
Lime (mt/ha)	–	0.51	–
Other inputs			
Gasoline (l/ha)	17	17	7
Diesel (l/ha)	514	271	663
Irrigation (m^3/ha)	9144	1523	8128
Processing energy			
Natural gas (m^3/mt)	238.0 (paste) 40.2 (diced)	238.0 (paste) 40.2 (diced)	238.0 (paste) 40.2 (diced)
Electricity (kW h/mt)	44.9 (paste) 7.7 (diced)	44.9 (paste) 7.7 (diced)	44.9 (paste) 7.7 (diced)
Transport distances			
Field to processor (1-way km)	97	209	34
Bulk product to re-manufacturer (1-way km)	3542	0	0
Packer to distribution center (1-way km)	370	370	3703

Table 6. Key characteristics of three tomato production systems and supply chains. Source: (Brodt *et al.*, 2013).

Component	Energy Use (MJ/kg)	Emission Rate (kg CO_2/MJ)
N	65	0.05
P	15	0.06
K	10	0.06
S	5	0.06
Lime	0.6	0.72

Table 7. Energy requirement to manufacture fertilizer components and the associated CO_2 emissions. Source: (Wells, 2001).

The absence of lime makes the California production system more greenhouse gas conservative because comparatively, the addition of lime in Michigan produces CO_2, which is responsible for about 10% of the total greenhouse gases associated with the Michigan tomato production. Regional differences further favor California as better land to grow tomatoes because of the higher comparative yields due to the dry climate and lower incidence of disease. Yields from California are about 20% higher per hectare in California than they are in Michigan due to favorable regional soil differences within California (Brodt *et al.*, 2013). The better energy and resources use efficiency per metric ton of tomatoes in California is balanced by the transport emissions and energy costs of long-distance transport.

Another life cycle assessment, by Saunders *et al.* (2006), provides a regional comparison of the energy used and CO_{2eq} emissions in the production of dairy, lamb, apples, and onions in the United Kingdom and New Zealand. In the United Kingdom, 43,879 MJ of energy is used per ton of milk solids compared to only 20,758 MJ per ton in New Zealand. Including the energy used to ship the dairy products by boat to the United Kingdom, New Zealand’s production is still much more energy efficient at 22,627 MJ per ton (Saunders *et al.*, 2006). The major difference in energy used results from the fact that

New Zealand uses a less intensive production system relative to that of the United Kingdom, which uses greater external inputs of concentrates and forage. In support of a total life cycle assessment to evaluate CO_{2eq} emissions, the United Kingdom emits over two times as much CO_2 as New Zealand even when considering the transport emissions involved in shipping to the UK. The United Kingdom emits 2,650 kg of CO_2 per ton of milk solids compared to 1,290 kg per ton in New Zealand (Saunders *et al.*, 2006). Sourcing dairy products locally within the United Kingdom would therefore be less environmentally friendly in terms of energy inputs and greenhouse gases even considering the transport emissions since shipping within the United Kingdom is done using trucks, which emit almost thirteen times more greenhouse gases per ton-km than ocean shipping (Table 8) (Wakeland *et al.*, 2011). Ton-km refers to a unit of freight carriage that is equal to transporting one metric ton of freight one kilometer. Although the distance from Italy to the United Kingdom is considerably less than the distance from New Zealand to the United Kingdom, displays that the transport energy from shipping from Italy to the United Kingdom is 3.68 times more energy demanding than shipping from New Zealand to the United Kingdom (Table 9). Additionally, the kgs of CO_2 emissions per ton-km are 4 times greater when shipping from Italy to the United Kingdom than they are for shipping from New Zealand to the United Kingdom.

	MegaJoules per ton-km	kg CO_2e per ton-km
International water-container	0.2	0.14
Inland water	0.3	0.21
Rail[a]	0.3	0.18[a]
Truck[b]	2.7	1.8
Air[c]	10	6.8

Table 8. Energy use and CO_{2eq} emissions per ton-km for different shipping methods. Source: (Wakeland *et al.*, 2011) based on data from Weber and Matthews (2008).

Transport Type	Energy Coefficient MJ per ton km	CO_2 Emission Coefficient (kg CO_2 per ton km)
Shipping (NZ to UK)	0.103	0.006
Truck (Italy to UK)	0.38	0.024

Table 9. Transport energy and CO_2 emission coefficients for international transport. Source: (Saunders *et al.*, 2006).

In a regional comparison of the production of apples in the United Kingdom and in New Zealand, the energy component of apples produced in New Zealand is lower than that from the United Kingdom. The energy intensity for New Zealand apples is 2,703 MJ per ton compared to 2,967 MJ per ton of apples from the United Kingdom (Saunders *et al.*, 2006) (Table 10). These numbers are inclusive of the transport and storage costs involved in bringing New Zealand apples to the United Kingdom. The carbon dioxide emissions per ton of apples in New Zealand delivered to the United Kingdom is 168 kg of CO_2 per ton of apples, compared to 181 kg of CO_2 per ton of apples in the United Kingdom (Saunders *et al.*, 2006). The CO_2 emissions per ton of apples produced are greater in the United Kingdom than in New Zealand because of higher energy use within the United Kingdom. Furthermore, the electricity generation in New Zealand is dependent on more renewable sources than it is in the United Kingdom, contributing to greater overall emissions in the United Kingdom relative to New Zealand.

Item	Quantity/hectare		Energy MJ/Tonne apples		CO_2 Emissions kg CO_2/Tonne apples	
	NZ	UK	NZ	UK	NZ	UK
Direct						
Fuel, Electricity and Oil – (L of Diesel equivalent)		794		2,337		152.1
Fuel use - Orchard (L of Diesel)	436		380		26.1	
Electricity Use (kWh)	1,180		192		3.7	
Direct subtotal	-	-	**573**	**2,337**	**29.8**	**152.1**
Indirect						
Nitrogen (kg)	80	78	104	362	4.8	18.1
Phosphorus (kg)	8	11	2	12	0.1	0.7
Potassium (kg)	60	55	12	39	0.7	2.3
Lime (kg)	1,042		13		9.0	
Herbicide (kg ai)	3.2	1.46	20	57	1.2	3.4
Fungicide (kg ai)	15.6	6.21	65	93	3.9	5.6
Insecticide - General (kg ai)	2.2	1.24	14	28	0.8	1.7
Insecticide – Oil (kg ai)	29.0	3.51	70	30	4.2	1.8
Plant Growth Regulator (kg ai)		0.17		2		0.1
Indirect subtotal	-	-	**300**	**624**	**24.7**	**33.8**
Capital						
Farm buildings (m^2)	2.0		1		0.1	
Tractors (kg)	248		22		2.0	
Light trucks/utilities (kg)	78		7		0.6	
Machinery (kg)	294		17		1.7	
Support Structures						
Posts (#)	400		4		0.3	
Wire (m)	8,000		7		0.8	
Irrigation (m)	2,147		21		0.0	
Capital subtotal	-	-	**78**	-	**5.6**	-
Total Production	-	-	**950**	**2,961**	**60.1**	**186.0**
Yield (tonnes)	**50**	**14**				
Post Harvest						
Cold storage (UK 6 months)	-	-		2,069		85.8
Shipping (NZ to UK) (17,840 km)	-	-	2,030		124.9	
Post Harvest subtotal	-	-	**2,030**	**2,069**	**124.9**	**85.8**
Total Energy Input/Emissions	-	-	**2,980**	**5,030**	**185.0**	**271.8**

Table 10. Total energy and carbon dioxide indicators for New Zealand and United Kingdom apple production. Source: (Saunders *et al.*, 2006).

Regional differences also affect the energy associated with onion production, which is 745 MJ per ton in New Zealand, compared with 615 MJ per ton in the United Kingdom. New Zealand however also has a higher CO_2 emission rate per ton of onions at

168 kg emissions per ton compared to 154 kg emissions per ton in the United Kingdom due to differences in energy sources (Saunders *et al.*, 2006). When shipping costs are included into the total energy inputs in New Zealand onion production, the energy total rises to 2,620 MJ per ton, much greater than the total of 615 MJ per ton in the UK. However, in order to provide year round locally sourced onions, storage of onions is necessary, which raises the UK energy costs to 3,411 MJ per ton (Saunders *et al.*, 2006). In this instance, it seems that when in season, it is more energy conservative to source onions locally, but when storage is needed, sourcing onions from New Zealand is a better alternative.

In the production of lamb, the energy used in New Zealand including transportation to the UK is only 9,632 MJ per ton of lamb, compared to 41,603 MJ per ton of lamb. The energy used in the life cycle of New Zealand lamb including transportation is only about 23% of that of the energy used in the UK, and as one might expect, the CO_2 emissions per ton of lamb is also lower for New Zealand at 624 kg CO_2 per ton compared to 2,585 kg CO_2 per ton in the UK (Saunders *et al.*, 2006). The difference in energy used between the UK and New Zealand is a result of the extensive production system in New Zealand compared to the UK.

3. FOOD STORAGE

3.1. Methods of Storage

Most places cannot grow food year-round, but the global food trade has accustomed many consumers to acquiring a variety of foods regardless of the season. There are several factors to consider when evaluating the environmental impacts due to the storage of food. In addition to the length of storage, the thermal qualities of a storage facility, the variety of products in a refrigerated case, the number of hours that a store or building is open per week, and the quantity of sales will all affect the energy use and length of time that food can be sufficiently stored (Edwards-Jones *et al.*, 2008). Although local foods may reduce and save transport related energy and emissions, the use of cold storage has the potential to increase the embedded emissions and energy involved in the life cycle of foods. For local commodities that would need cold storage to maintain their freshness and meet consumer demand for local food during the winter or off-season, storage can increase energy demand beyond those saved through sourcing foods locally (Michalský and Hooda, 2015)

Commercial apples for example are often stored in a chilled and modified atmosphere for 3-12 months before they are sold in order to ensure both freshness and a supply of local apples year round (Hoskins and Lobstein, 1999). However, from a primary energy use perspective it is only favorable to purchase local apples that have been stored for less than 4 months, compared to buying fresh imported apples (Llorenc *et al.*, 2007). This is due to the fact that storage can demand a great deal of energy, resulting in greenhouse gas emissions. For example, to ensure that local onions were available to consumers in the United Kingdom, storage was implemented and was responsible for 80% of the energy and 73.6% of the total CO_{2eq} emissions involved in the life cycle of the onions (Saunders *et al.*, 2006). In another instance, Mundler and Rumpus (2012) found that on-farm storage alone could represent over 20% of the calculated energy consumption involved in the life cycle of various food products.

The time of year during which local apples are consumed also affects the need for storage and importation of non-local apples. If a country can grow fresh apples year round, their need for storage will be greatly reduced (Figure 3). The ability to grow fresh apples year-round will be affected by the local climate, seasons, and hemisphere in which a country lies. A lack of continuous availability of fresh local apples is important as there will be a storage loss (food spoilage) as a function of time; Llorenc *et al.* (2007) found this loss to be anywhere from 20 to 40 percent. This means that between 1.25 kg and 1.4 kg of food would need to be stored for there to be 1 kg of food provided to customers. It was also found that the remaining apples had a lower quality than the fresher imported apples.

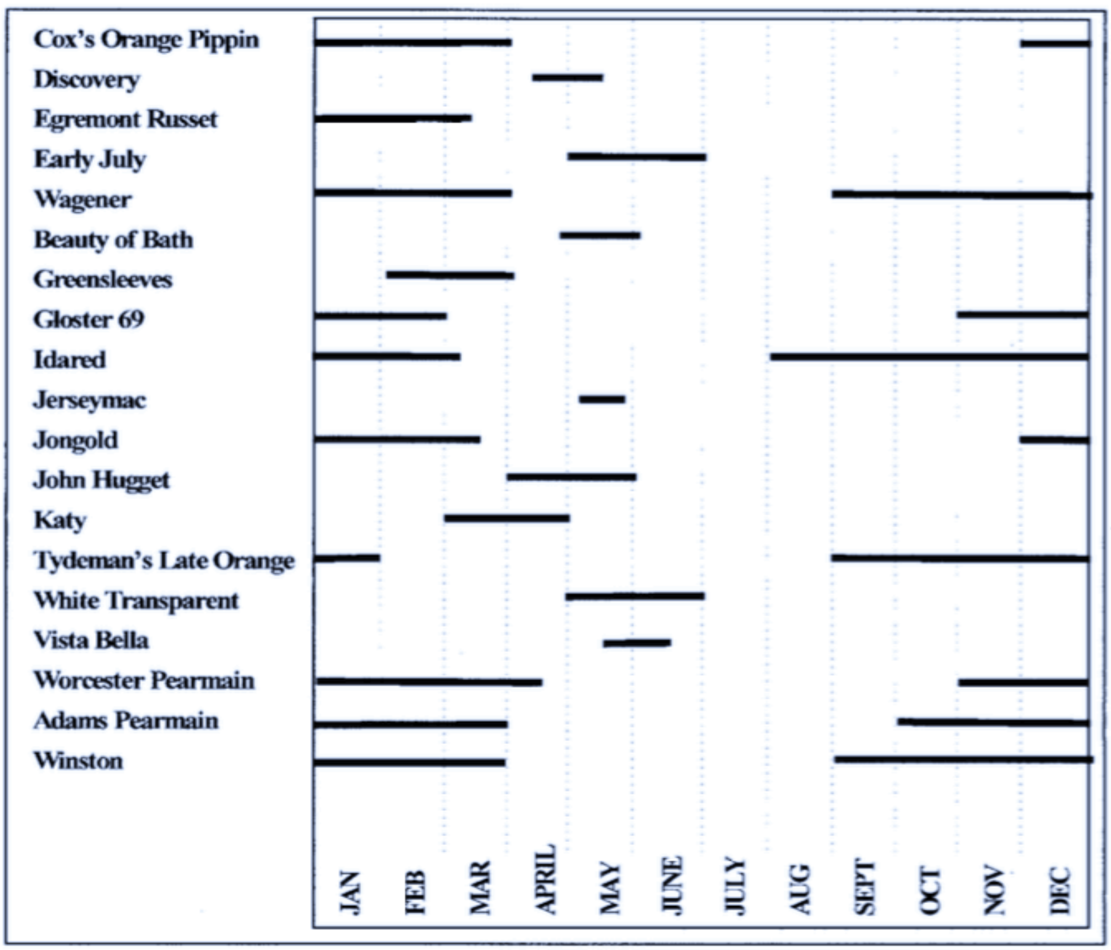

Figure 3. The seasonal availability of a selection of British apples. Source: (Jones, 2002).

Food freshness and quality are essential factors for customers however, and less fresh food is not as appealing to customers and therefore will not be as likely to be bought when a fresher alternative is available at a similar price. As such, there is a balance between the energy needed to store food, food quality, food loss over time and the energy needed to import fresh food. However when comparing long-term storage of local produce to sourcing local produce year-round through protected cultivation, the long-term storage through freezing or refrigeration of local produce provides a more environmentally friendly option (Milá *et al.*, 2008).

In order to buy local food year-round in many areas of the globe, there would need to be a great increase in the storage time of food, which is energy intensive in itself as it may require refrigeration or other preservation methods. One alternative option to increasing storage of food to meet consumer demand for local foods would be to combine seasonal availability with different modes of preservation and processing in order to reduce the energy needed when storing produce. Canning or bottling of fresh foods for example could be a viable tactic for providing local produce throughout the year, without the energy expenditures needed to refrigerate or freeze food long-term, but yet again this is oftentimes at the expense of quality. Even when considering the CO_{2eq} emissions from transportation of food, it can still be more economic to transport food long distances than to store them long-term since food-related transport emissions can be less than 10 percent of the total life cycle emissions (Smith, 2005; Sim *et al.*, 2007; Canals *et al.*, 2007; Avetisyan *et al.*, 2014).

3.2 Food Processing

Processing of food can take place for reasons ranging from improving shelf life to making an entirely different consumer product. The processing steps for food items will contribute to the amount of energy used. In this section, a comparison of the CO_{2eq} emissions between tomato paste and diced tomatoes, frozen and fresh broccoli, and frozen and fresh beans will be used to display how processing can affect emissions.

Although not comparable from a consumer perspective, the differentiation between tomato paste and diced tomatoes made by Brodt *et al.* (2013) is useful to highlight some important differences that result due to processing steps. On a per kg basis, tomato paste has 2 times more environmental impact than diced tomatoes due to the larger amount of tomatoes needed to make an equivalent weight of tomato paste and due to the high energy demand needed to heat and evaporate tomatoes to make paste. This brings up an interesting point related to transport emissions. If 4.5 kg of tomatoes is used to make tomato paste, then processing of tomatoes closer to the field should reduce transport related emissions, as compared to transporting the same 4.5 kg further to be processed elsewhere. If you process them closer to the source, then you can reduce total transport weight of raw food product, therefore reducing emissions.

As shown in Figure 5, the emissions involved in the life cycle of tomato paste are greater in all scenarios than for diced tomatoes. The total life cycle greenhouse gas emissions from 1 kg of tomato paste are between 47 and 60 percent greater than the emissions per 1 kg of diced tomatoes. If compared from a serving-size basis as displayed in Figure 6, canned tomatoes are about twice as greenhouse gas intensive as is tomato paste. This is due to the fact that a serving of paste is 33g and a serving of diced tomatoes is 122g. This shows how the processing and production involved in the life cycle assessment of food contribute to differences in greenhouse emissions, which would be overlooked in a food miles scenario.

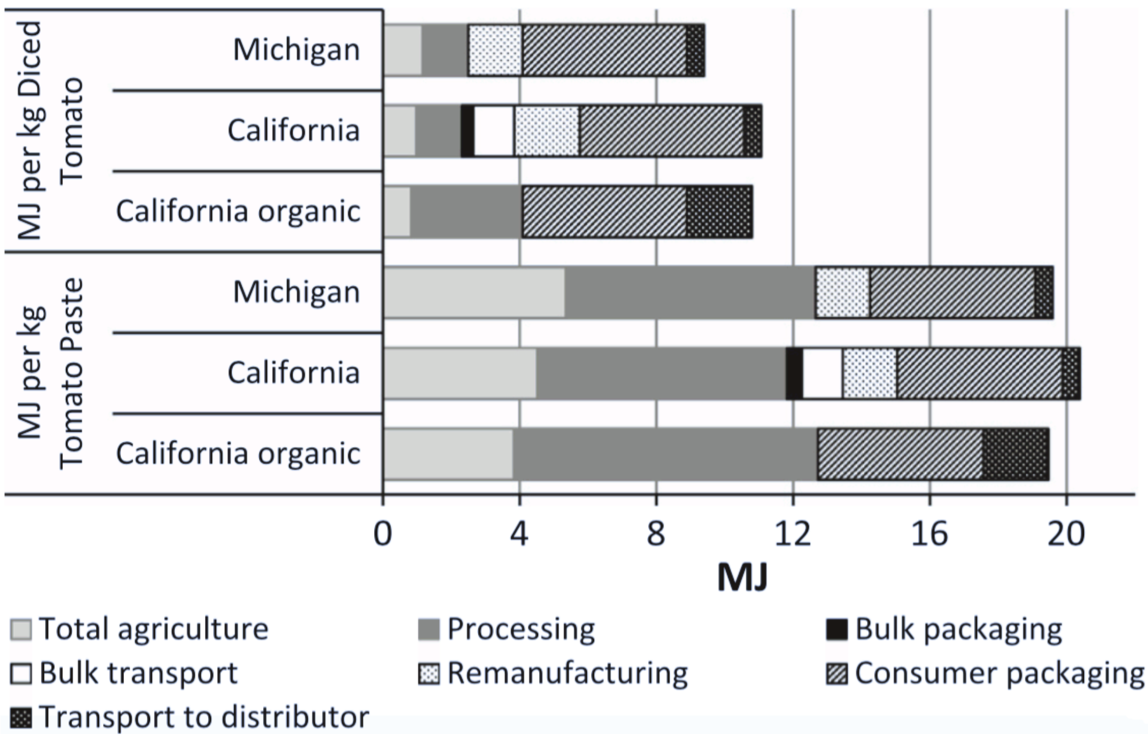

Figure 4. The life cycle energy consumption per kg of diced tomato and per kg of tomato paste. Source (Brodt *et al.,* 2013).

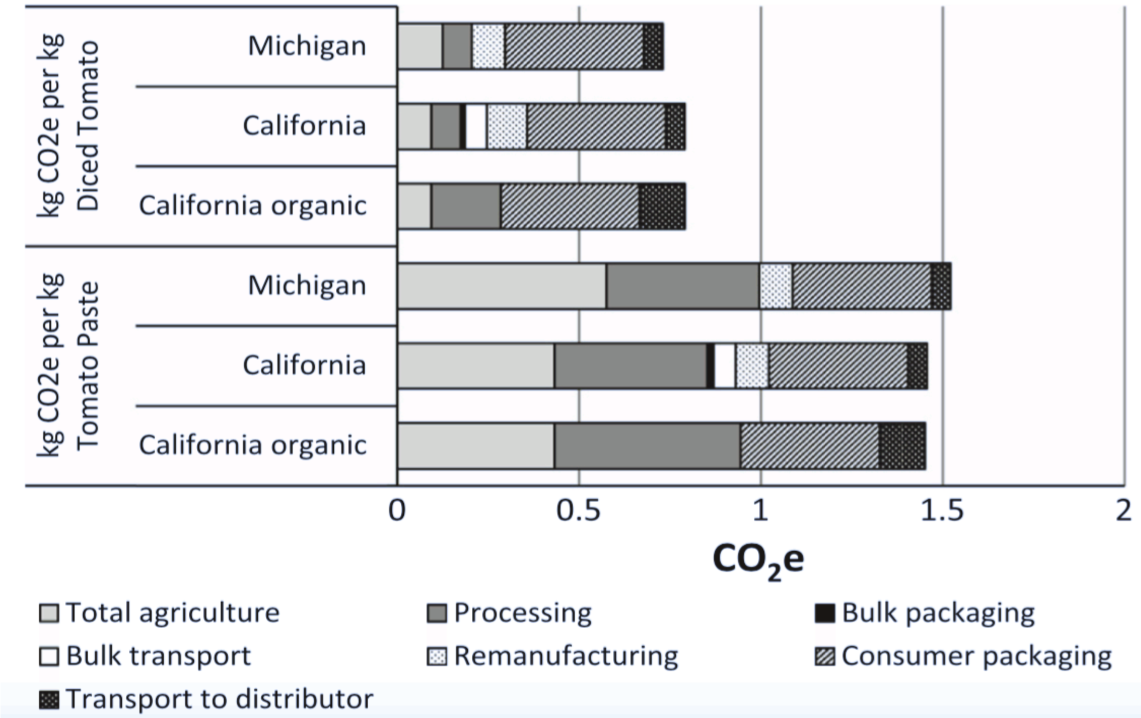

Figure 5. The life cycle CO_{2eq} emissions per kg of diced tomato and per kg of tomato paste. Source: (Brodt *et al.,* 2013).

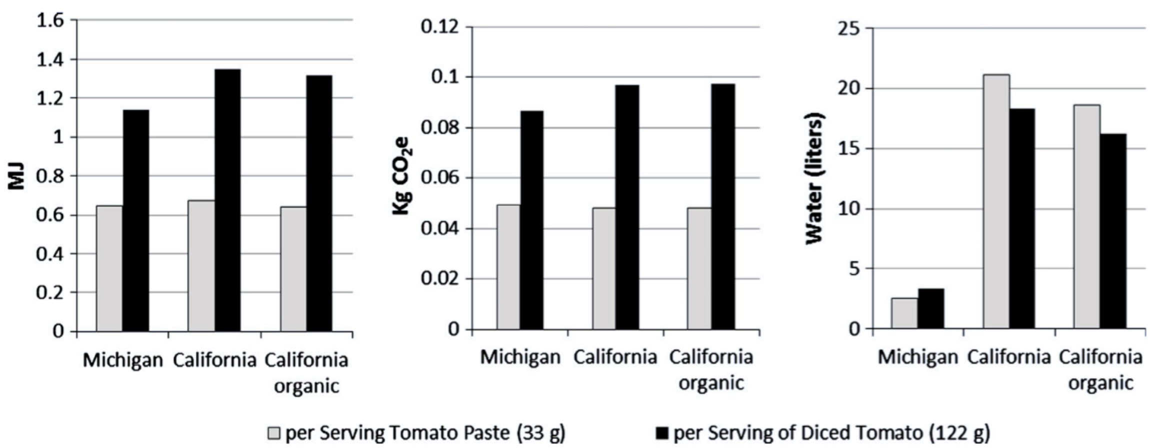

Figure 6. A comparison of the life cycle energy consumed (MJ), CO_{2eq} emissions released (Kg), and the water used (L) for tomato paste and diced tomatoes on a per-serving basis. Source: (Brodt *et al.,* 2013).

Product	Units	California Truck only	California baseline (Truck and Rail)	Michigan baseline (no long distance transport)
Paste (1 kg)	MJ	23.1	20.4	19.6
	kg CO_{2eq}	1.65	1.46	1.5
Diced (1 kg)	MJ	13.8	11	9.36
	kg CO_{2eq}	0.99	0.795	0.711

Table 11. The total life cycle energy use and greenhouse gas emissions by choice of long-distance transportation mode. Source: (Brodt *et al.,* 2013).

Post-harvest processing, such as freezing foods, is an important contributing factor in the life cycles of some food products. In an analysis by Milá *et al.* (2008) comparing frozen British broccoli, fresh British broccoli, and fresh Spanish broccoli, the transport and retail of British frozen broccoli used 8 times as much energy as fresh British broccoli, and 3 times as much as Spanish fresh broccoli even when the latter was transported from Spain. This is an instance where the use of food-miles would be an inaccurate metric to evaluate the carbon footprint from food. However, it is important to note that retail time for frozen broccoli is longer than fresh broccoli, which partially explains the higher energy use. The main reason for increased CO_{2eq} emissions for frozen broccoli is due to post-harvest processing, frozen storage in wholesale and retail, and frozen storage at home. The energy used per ton of fresh produce sold ranged from 115.94 MJ per ton to 150.56 MJ per ton, compared to the energy involved in frozen food processing, 539.85 MJ per ton (Brodt *et al.,* 2013). The frozen processing stage in this study is at a minimum 3.58 times greater in terms of energy used than the energy used in the fresh food processing stage. Similar results were found for frozen beans, which were found to demand 2.94 times more energy per ton of produce than their fresh counterpart.

In terms of kg CO_{2eq} emissions, the average emissions for fresh broccoli from two British farms is 2.08 kg CO_{2eq}, whereas frozen broccoli is 2.64 kg CO_{2eq} (Milá *et al.*, 2008). Therefore, when fresh British broccoli is in season, buying and consuming fresh British broccoli is the least in terms of emissions, however if the choice is between frozen British broccoli and fresh Spanish broccoli, the results are not as obvious. The comparison of fresh Spanish and frozen British broccoli is pertinent because both of these produce options are available for British consumers during the same time of year (November to April). This study shows how distance was not necessarily the determining factor for the total CO_{2eq} emissions, and that the intermediate steps involved in processing of food were necessary to evaluate the carbon footprint of the food products.

3.3 Food Packaging

Packaging food is yet another example of a step involved in the life cycle of food that would be unaccounted for using the food-miles analysis. From an economic standpoint it is more efficient to package food at the point of production even though extensive packaging adds both weight and volume to the product (Twede *et al.*, 2000). From an environmental standpoint, it is most efficient to make the cargo load as lightweight as possible to reduce transport emissions, which would support packaging food after the transportation stage. Point (2008) performed a life cycle assessment on wine and found that the largest contribution to emissions was due to the production and transport of the bottles themselves. Due to the fact that by weight and volume, only about 50 percent of the wine bottle is actually product, a large portion of energy is used to transport heavy glass wine bottles (Constar, 2010).

The potential for reducing emissions is great, and changing the packaging used for food and beverages was found to help reduce overall greenhouse gas emissions by 41 percent (Constar, 2010). Solutions such as technological advancements and improvements in the packaging industry could help minimize the energy requirements of these stages of the life cycle of food and a good alternative could be to change the form of food so that it requires less packaging. Additionally, changing customer preference towards purchasing foods with less packaging or that use more sustainable packaging, could prove to be beneficial in the reduction of total energy used.

In an analysis of the energy used in the Swedish food supply system, 16% of the total energy was used for the processing of food products and 12% of the total energy was used for the packaging of food products (Wallgren and Höjer, 2009). Together, the processing and packaging stages represent 28% of the total energy used in the Swedish food supply system. If this food system were analyzed through the scope of food-miles, over a quarter of the total energy and their associated emissions would go unaccounted. This shows the need to consider all of the inputs and outputs involved in the entire life cycle of food production.

4. FOOD DISTRIBUTION

4.1 Food Supply Chain Structures and Logistics

Advocates of food miles argue based on the premise that the further that food is grown from where you buy it, the worse it is for the environment due to the energy and greenhouse gas emissions involved in the transportation process. However, King *et al.* (2010) has shown that the fuel use in transportation is affected more so by supply chain structure and the size and numbers of segments than by the distance traveled by the food product. If in fact the largest portion of greenhouse gases emissions is directly from the transportation of food products, then the food miles argument would seem to be valid. If however, the largest cost in terms of emissions and energy comes from other steps in the food acquisition process such as customer travel to the market to obtain food, then there should be more of an emphasis on reducing customer travel, instead of reducing food miles.

Local sourcing of food can minimize energy expenditure due to the transportation of food in cases where there is no transportation of the food to stores, such as in cases where farmers sell directly to customers. Consumer transport costs could also be avoided altogether in cases where shopping is carried out on foot or bicycle (Jones, 2002). However, even in the United Kingdom where 80% of consumers live within walking distance of a food retailer, 45% of urban consumers and 95% of rural consumers still use their cars to buy food (Johansson and Holmberg, 1991). Coley *et al.* (2009) calculated that the threshold distance over which a consumer can drive that makes a local food sales chain's energy efficiency less favorable than a long-chain system is 6.7 km. Mundler and Rumpus (2012) calculated that the average consumer car trip length for food is 5.85 km, which is less than the threshold value previously stated, making the average trip for locally sourced foods more favorable in terms of emissions than a trip for non local foods. Although, in cases where customers travel more than 7.4 km to buy local foods, a mass distribution system approach is a less energy and greenhouse gas intensive option (Coley *et al.*, 2009). The most conservative method, in terms of greenhouse gas emissions, for obtaining food seems to be a food basket delivery system within a city, wherein the customers received home deliveries of their groceries (Mundler and Rumpus, 2012).

4.2 Small-scale versus large-scale logistics

One benefit of the specialization, centralization, and globalization of the food market is that shoppers have access to a year-round supply of fresh produce regardless of the location and timing of its production (Sundkvist *et al.*, 2001). In a comparison of small-scale to large-scale systems, the majority of emissions were from the final delivery stage of food to customers using light goods vehicles, not from the chilling or mass transportation stages using heavy goods vehicles, which makes up a larger proportion of the miles travelled in the life cycle of the food products. In this large-scale box delivery system, the final light goods vehicle distribution accounted for 50% of the total system emissions, whereas the heavy goods transportation stage only accounted for 25.7 % of the emissions total (Coley *et al.*, 2012). Saunders and Hayes (2007) found that when comparing local small-scale retailers to more mainstream retailers, the shorter travel distance in local retailers was actually offset by the greater transportation efficiency in the mainstream retailer, resulting in a lower energy use per amount of food product transported by the mainstream retailer (Martinez *et al.*, 2010). In these instances, it would be more environmentally friendly to improve energy use efficiency and reduce greenhouse gas emissions through the use of hybrid vehicles or alternative delivery systems. This is important evidence for moving away from the food-miles thought process, focusing less on total distance and more on the totality of elements involved in the life cycle of food.

One of the possible issues with small local producers and small-scale distribution systems is that they can lack the economic means to buy the most energy efficient technologies when compared to a larger-scale company. The scale of food chains and distribution can affect the CO_{2eq} emissions and smaller scale food chains typically have greater greenhouse gas emissions than larger scale chains. This is mainly due to the fact that food transportation by these types of industries usually takes place in smaller and less efficient trucks, whereas large-scale industries typically use large trucks and economies of scale to save energy and reduce greenhouse gas emissions (Van Hauwermeiren *et al.*, 2007). Using many small vehicles that transport low volumes of food is less efficient in terms of fuel used and volume of food transported (Redlingshofer, 2008).

Transporting larger volumes of food is much more energy efficient than moving smaller volumes the same distance. Some sources have even found that per unit product, fuel use is smaller in supermarket supply chains than in local supply chains (King *et al.*, 2010). In a case of local bread production for example, localization of bread production actually resulted in higher overall energy use as the energy requirement for producing bread was between 7.1 and 14.8 MJ/kg of bread, decreasing with increasing size of a bakery (see Figure 7) (Sundkvist *et al.*, 2001). This is a good example of how small-scale local operations may be less energy and resource efficient due to the principle of economy of scale. It also shows that in order to make an informed decision regarding the sustainability of food production, the analyses of several factors in addition to distance is necessary.

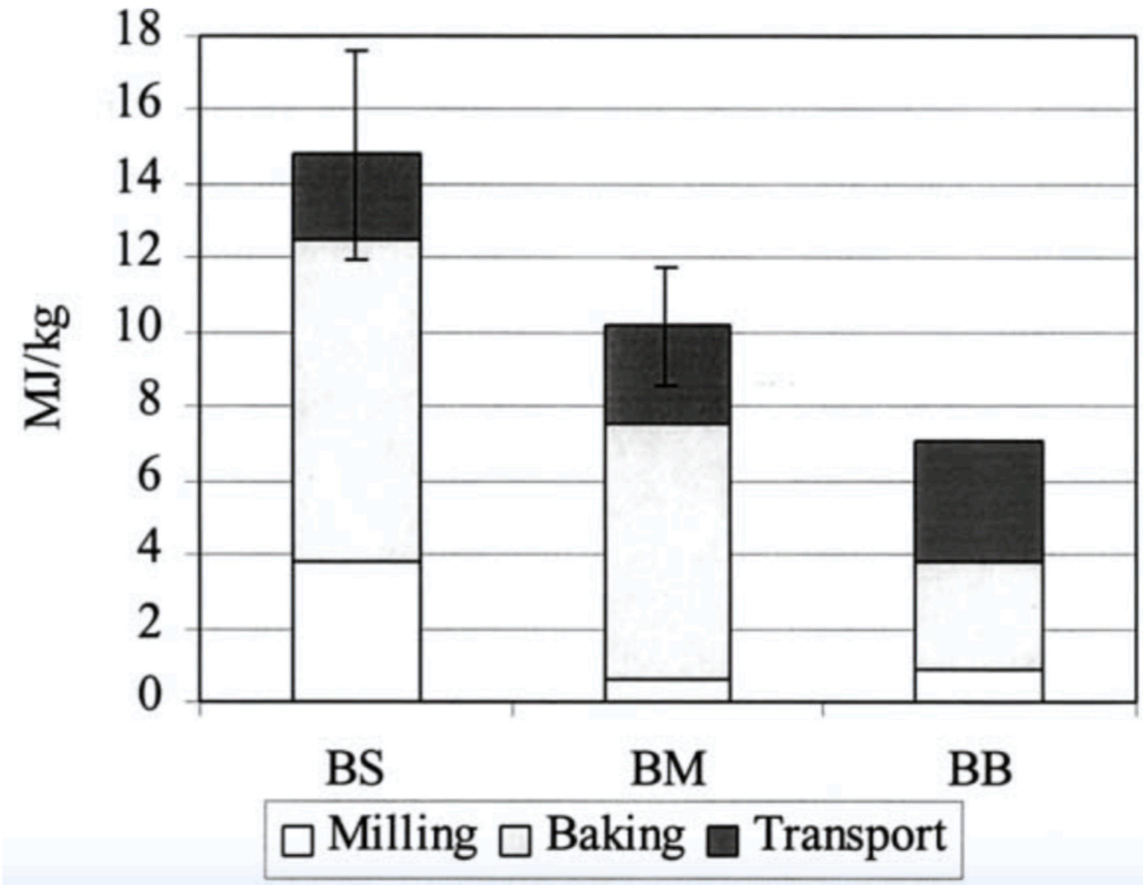

Figure 7. The energy requirements for producing 1 kg of bread in the different size bakery categories (BS- Bakery small, BM- Bakery medium, BB- Bakery big). Error bars indicate standard deviation. Source: (Sundkvist *et al.*, 2001).

4.3 Food Delivery to Customers

One method through which consumers can obtain food is a home-delivery scheme. According to a study by Jones (2002) substituting imported apples purchased at a grocery store with local apples that are delivered through a home delivery alternative could reduce CO_{2eq} emissions by 96%. The CO_2 emissions involved in the life cycle of the apples up to the point of customer interaction was much lower when the apples were delivered (14.51 kg CO_2 per ton of apples) than when the apples were transported to a store and then purchased by a customer (363.78 kg CO_2 per ton of apples). Coley *et al.* (2009) showed through a case study examining an organic vegetable farm, where the consumers went to the markets to buy their products, that there were actually more greenhouse gas emissions originating from the travel to the markets than would have resulted had a large-scale supply chain associated with a larger food retailer delivered the vegetables to their homes. These results suggest that instead of focusing on reducing food-miles, a reduction in the CO_{2eq} emissions involved in the life cycle of food could be achieved through more efficient delivery methods.

Wakeland *et al.* (2011) found similar results that direct-to-consumer local delivery of wine was the most energy efficient distribution method because it resulted in less overall transportation distance. In contrast, a consumer trip via car to obtain wine produced 80 times more emissions than the home delivery of wine to customers. In support of this alternative to traditional distribution methods, it was found that the final link in the food supply chain between retailer and consumer can be the most greenhouse gas intensive step in the life cycle of food (Browne *et al.*, 2005; Van Hauwermeiren *et al.*, 2007). Figure 8 displays results that are in accordance with these findings, and shows that the most energy-intensive transit link is often the last step, driving to the store. Delivery of food to customers could be a more sustainable solution to traditional shopping as it generated the lowest amount of emissions among all transport categories, contributing just 90.72 CO_2 per kg of fruits and vegetables studied (Michalský and Hooda, 2015).

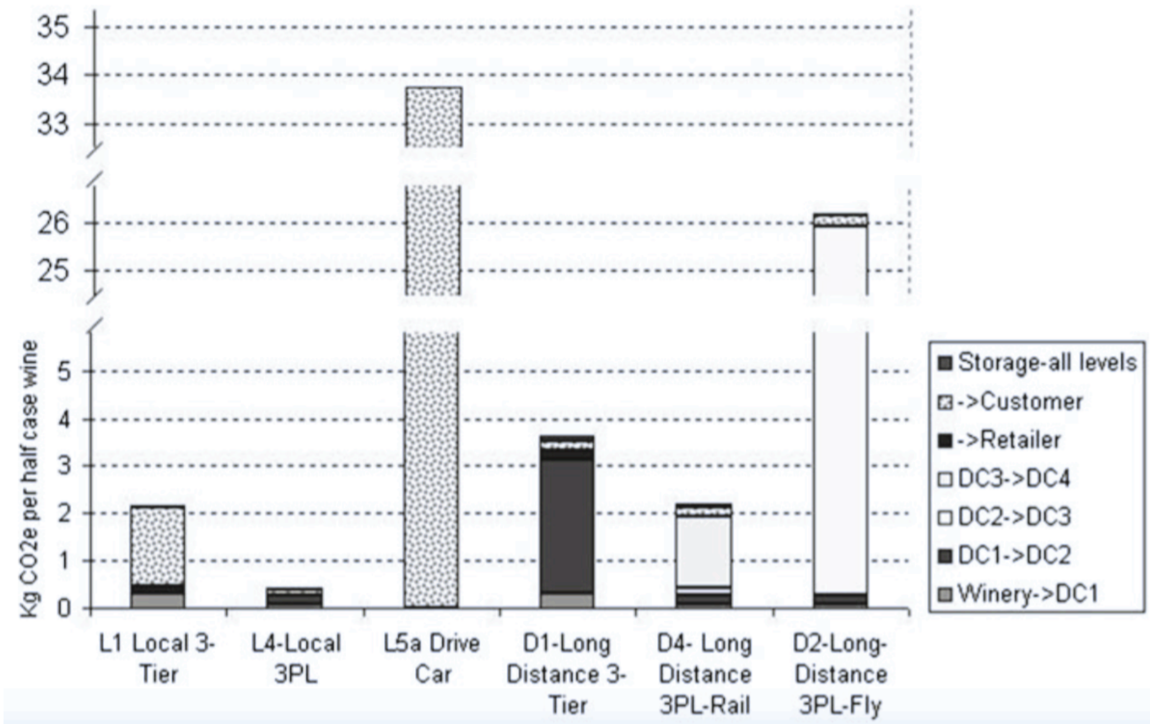

Figure 8. CO_{2eq} emissions for local and long distance delivery scenarios. Source: (Wakeland *et al.*, 2011).

4.4 Modes of Transportation

In the United States and many other developed countries, transportation is the largest end-use contributor toward global warming. According to the United States Department of Energy, CO_2 emissions resulting from transportation exceeded 2.2 billion tons in the year 2007 (DOE, 2009). Although transportation generally does not have the largest environmental impact in food supply chains, it can play a significant role depending on the specific supply chain and the modes of transport used. Distributing produce by plane for example is 10 times more energy intensive than distribution by road, which is, in turn, 6 times less energy efficient than shipping by boat. If food products are to be distributed over long distances, then based on these comparisons of the direct energy consumption, preference should be given to distribution by boat (Jones, 2002).

This section considers the transport related emissions from major life cycle phases of food products in United States. Even though half of all fruit sold in the United States is imported and, on average, produce grown in North America travels 2,000 km, transportation of food accounts for only 6 percent of the life cycle emissions within the United States food sector (Figure 9) (Pirog *et al.*, 2001; Wakeland *et al.*, 2011). Based on Figure 9, production and processing dominate the CO_2 emissions at 81.6 percent, followed by cooking at 8.3 percent (Wakeland *et al.*, 2011). In accordance with these findings, shifting the focus away from reducing food miles towards finding more sustainable production and processing methods could yield greater potential reductions in emissions. Another study by Weber and Matthews (2008) shows similar findings that aggregate transportation only makes a small contribution of 11 percent to the total CO_2 emissions involved in the life cycle of food products.

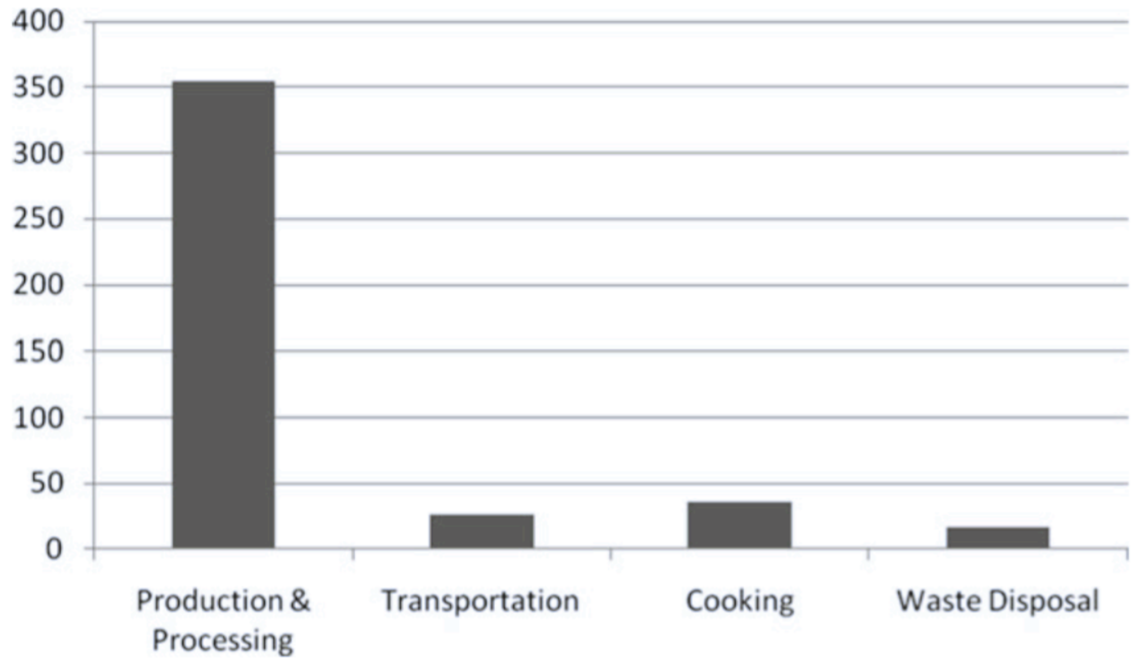

Figure 9. Life cycle carbon emissions (millions of metric tons of CO_{2eq}) for different stages of the food life cycle for major food categories in the United States: (Wakeland *et al.*, 2011).

One issue with traditional measures of transportation metrics, and a reason for increasing the scope of life cycle assessment parameters, is that the importing country does not account for the environmental impacts and greenhouse gas emissions associated with the export of a product. Meaning that when a product is imported into a country, the importing country does not include those emissions into the life cycle of the product, and in many cases, the life cycle emissions accounting only occurs within a country's national boundaries. Therefore, national figures may show decreasing emissions for countries importing more food because the greenhouse gas emissions generated by international airfreight for example are not contained within the country that initiates the trade. This is an issue of scale of current standard procedures for life cycle assessments, and is further justification for why food supply chains need to be considered in their entirety (Jones, 2002; Michalský and Hooda, 2015)

The contribution of food transportation to greenhouse gas emissions can be significant and there is an increasing trend in both the volume and distance of international transport (Sundkvist *et al.*, 2001). In France, for example, the transport sector emits 27% of total greenhouse gas emissions. The transport of food is important to the transport sector as food transport makes up about 21% of the transport sector's total tonnage (CAS, 2007). The means by which food is transported affects the CO_{2eq} emissions involved in the life cycle of food since energy expenditure efficiency and greenhouse gas emissions are not the same for all modes of transportation.

4.4.1. Airfreight

To meet the needs and demands associated with a global fresh food supply chain, airfreight is used as it is the fastest way to deliver a product over a long distance, however the convenience of flying foodstuffs is at the expense of the environment. The use of planes to import food has increased over time and in the United Kingdom between 1980-1990, the import of fish and fruits and vegetables increased by 240% and 90% respectively. Between 1990-1998, the import of fruits and vegetables by plane more than tripled (Jones, 2001; DOT, 1991). Reducing the airfreight food miles would be beneficial to reducing transport related emissions because although airfreight transportation of food accounts for only 1% of food ton kilometers and 0.1% of vehicle kilometers, it produces 11% of the food transport CO_{2eq} emissions (Sim *et al.*, 2007). In addition to low energy efficiency, the magnitude of pollution due to airfreight is quite significant compared to other modes of transportation. The IPCC has stated "the total radiative forcing due to the greenhouse gases from aviation is probably three times that due to carbon emissions alone. This contrasts with factors generally in the range of 1-1.5 for most human activities"[1]. To put this in perspective, consider the fact that a 2-minute DC10 Jet take-off produces the same amount of nitrogen oxides as driving 21,539 cars one mile at 30 miles per hour (Sustain, 1999). Considering that between 1992 and 2002, the air food miles distance that food has travelled doubled, there is need for a focus on reducing the use of planes to transport food given their magnitude of emissions release (Saunders *et al.*, 2006).

Compared to other forms of transportation, airfreight is the most environmentally damaging form of transportation in terms of CO_2 emissions per ton, as it can produce between 40 and 200 times the CO_2 emissions of marine transport (Saunders *et al.*, 2006; Sim *et al.*, 2007). For example, cherries imported from North America had the highest emissions relative to the amount of product transported due to the fact that they were delivered via airfreight. On the other hand however, when comparing apples imported from New Zealand to local apples, the apples from New Zealand traveled a greater distance comparatively, but had lower emissions because they travelled in a more efficient manner by sea freight (Saunders and Hayes, 2007).

The disproportionately high emissions impact of air transport makes up 11% of the total United Kingdom transport emissions, while only consisting of about 1% of the total food ton-km within the United Kingdom (Garnett, 2006; AEA, 2005). Similarly,

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[1] Intergovernmental Panel on Climate Change (IPCC) (1999). *Aviation and the Global Atmosphere*. Cambridge University Press, Cambridge.

when studying the importation of green beans via plane from countries like Guatemala and Kenya into the United Kingdom, there are immense differences in the carbon footprints and global warming potential of imported beans and local beans. Jones (2006) provides statistics on the differences between imported and domestic green beans, and shows that even though the energy requirements for production and packaging of green beans is similar between Kenya and the United Kingdom, the airfreight component involved in transporting the beans to the United Kingdom causes the energy footprint to be 12-13 times that of green beans from the United Kingdom. African supply chains have a greater environmental impact per kg of beans than the supply chain within the United Kingdom due to the long distance transportation of beans via airfreight (Milá *et al.*, 2008). In this instance, the primary energy and greenhouse gas emissions involved in the life cycle of the green bean supply chain from Africa is dominated by the transportation stage due to jet fuel consumption for airfreight (Milá *et al.*, 2008). One reason for the airfreight of food is due to the highly perishable nature of certain food items. Flying food may also be necessary in regions such as Africa where no other viable alternative exists for transporting produce to market.

In a similar study, the global warming potential of beans imported from Guatemala and Kenya into the United Kingdom was 20-26 times greater than that of beans from within the United Kingdom. The stark contrast in global warming potential between the imported and British beans is related to the fact that between 89 and 90 percent of the global warming potential of the imported African beans is due to emissions from shipping by airfreight (Sim *et al.*, 2007). It is worth noting that for these imported supply chains, 77-80% of the global warming potential is a result of using jet fuel in air transportation, while the use of electricity for the manufacture and recycling of in-flight boxes for food is transported in, makes up about 4-10% of the global warming potential associated with the life cycle contributions of airfreight (Sim *et al.*, 2007). The transportation aspect involved in imported supply chains from Kenya and Uganda to the UK constitutes over 95% of the energy used in the life cycle of the imported beans, but is related to how the beans were transported, not the total food-miles (Milá *et al.*, 2008). These are just a few examples of how the mode of transportation used to import and transport food can make an enormous difference in the energy use and greenhouse gas emissions in the life cycle of food.

In an analysis of various non-European fruits and vegetables imported into the UK, 1.4% of the total volume of fruits and vegetables imported were responsible for 20.3% (132,498 tons CO_{2eq}) of the total air emissions. To put this in perspective, this is equal to 46.7% of the combined emissions generated in the United Kingdom from both the production and transport stage of fruits and vegetables (Michalský and Hooda, 2015). This same study also analyzes the air importation of peas into the United Kingdom. The airfreight of peas into the United Kingdom generated 72.7% (88,295 tons CO_{2eq}) of the total air import emissions recorded for the non-European selected fruits and vegetables, compared to a significantly lower 992 tons CO_{2eq} emitted from the import of European peas. On a per ton basis, the emissions from airfreighted non-European peas are almost 59 times that of the emissions from the import of European peas using heavy goods vehicles (trucks) (Michalský and Hooda, 2015). Figure 10 shows the amount of CO_{2eq} emitted during each stage involved in the life cycle of food by region. On a per ton basis, the emissions from air transport of non-European fruits and vegetables was calculated to be 8,600.02 kg CO_{2eq} per ton, compared to emissions ranging between 88.54 kg CO_{2eq} per ton and 99.43 kg CO_{2eq} per ton depending on the type of vehicle used (Michalský and Hooda, 2015).

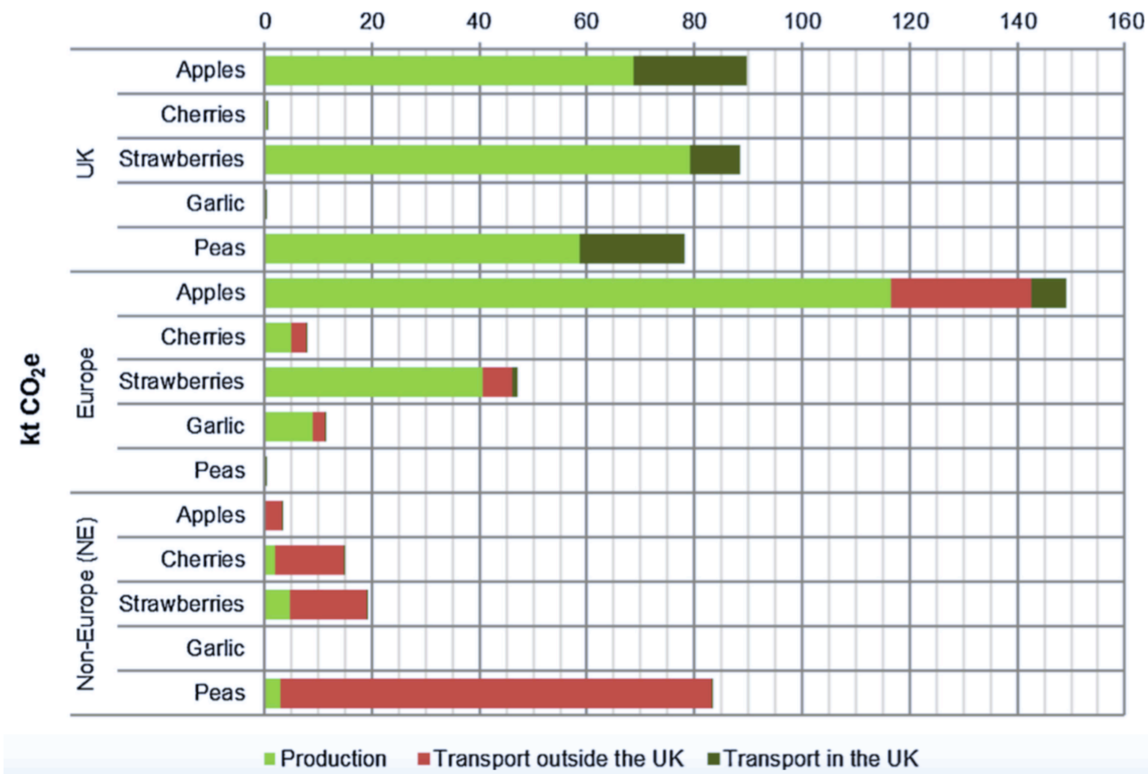

Figure 10. The total CO_{2eq} emissions generated by the production and relevant transport stages given for the selected fruit and vegetable commodities in 2013. Source: (Michalský and Hooda, 2015).

The food-miles argument is the idea that the further the distance between the place of food production and consumption, the greater the amount of emissions that will be involved in the life cycle. In support of this argument, Table 12 shows that the airfreight emissions for fruits and vegetables that are imported from non-European countries are generally lowest for countries that are comparatively geographically closer to the United Kingdom. For this specific case, in support of sourcing foods locally, or even within Europe, if the volume of fruits and vegetables air-freighted to the United Kingdom (12.79 thousand tons) was replaced by locally produced fruits and vegetables, emissions would be 20 times lower than the emissions due to the non-European production and air transport of fruits and vegetables (Table 13) (Michalský and Hooda, 2015). Due to the fact that importing fruits and vegetables into the United Kingdom via airfreight results in an additional 9.48 kg CO_{2eq} emissions on average for each kilogram of non-European fruits and vegetables, replacing the food imported by airfreight with locally sourced goods could help mitigate climate impacts. Buying a kilogram of each fruit and vegetable considered in the study by Michalský and Hooda (2015) (5kg total) would result in a savings of 51.83 kg CO_{2eq} in total.

Air transport stage (kg CO_2e/kg commodity)						
Commodity	Asia	MENA[a]	Sub-Saharan Africa	North America	South America	Weighted average
Apples	–	–	11.82	7.77	14.55	12.189
Cherries	22.30	4.95	11.82	7.72	15.06	11.254
Strawberries	–	4.69	–	7.77	13.34	5.938
Garlic	10.72	–	–	–	–	10.718
Peas	9.12	4.67	10.00	7.78	11.79	10.212

The air transport emissions of all non-European commodities were calculated using average kg CO_2e/kg value weighted by the amount of volume produced by each exporting country of each region.
[a] MENA – the countries of Middle East and North Africa.

Table 12. The embedded emissions from the air transport stage of fruit and vegetables imported from non-European countries, showing the influence of exporting countries. Source: (Michalský and Hooda, 2015).

Embedded emissions (kg CO_2e/kg commodity)				
Commodity	Production	Transport outside the UK	Transport in the UK	Total
UK (transported by LGV)				
Apples	0.320	–	0.098	0.418
Cherries	0.320	–	0.098	0.418
Strawberries	0.840	–	0.098	0.938
Garlic	0.570	–	0.098	0.668
Peas	0.290	–	0.098	0.388
Total	2.340	–	0.488	2.828
Weighted average	0.404	–	0.098	0.502
Europe (transported by HGV)				
Apples	0.430	0.097	0.024	0.550
Cherries	0.430	0.223	0.024	0.676
Strawberries	1.060	0.144	0.024	1.227
Garlic	0.680	0.171	0.024	0.874
Peas	0.400	0.174	0.024	0.597
Total	3.000	0.807	0.119	3.926
Weighted average	0.512	0.110	0.024	0.645
Non-European countries (transported by aircrafts)				
Apples	0.880	12.189	0.024	13.093
Cherries	0.880	11.254	0.024	12.157
Strawberries	1.390	5.938	0.024	7.352
Garlic	0.680	10.718	0.024	11.421
Peas	0.400	10.212	0.024	10.635
Total	4.230	50.310	0.119	54.659
Weighted average	0.661	9.480	0.024	10.164

Table 13. The embedded CO_{2eq} emissions of food commodities (Michalský and Hooda, 2015).

4.4.2. Road Freight

As stated previously, the method of transportation used for food affects the greenhouse gas emissions in the life cycle of food. Replacing rail shipping with truck shipping for example would result in 4 times more energy use for this portion of transportation and increase the total greenhouse gas emissions 13 to 25 percent depending on the food product (Brodt *et al.*, 2013). In this previous example, the change in transport mode alone would lead to favoring the use of products from across the country over locally produced food.

Comparing trucks to ocean shipping is an example of how shipping method affected overall emissions. Ocean transport produces low transport emissions of 0.14 kg CO_{2eq} per ton-km of freight compared to trucks, which have emissions that are almost 13 times greater than that of shipping at 1.8 kg CO_{2eq} per ton-km of freight (Wakeland *et al.*, 2011). Foods imported by ocean need road transport to and from the ports, which generates an amount of emissions that are similar to that of ocean shipping even though ocean shipping takes place over much longer distances. The lack of incorporation of the different magnitudes of impact for transportation methods is a key reason that food miles is not a correlative metric for the greenhouse gas emissions involved in the life cycle of foods.

The amount of food transported by roads is very large in certain instances, with over 98 percent of foodstuff movement by road in the United Kingdom. Comparatively, for all other commodity groups in the United Kingdom, an average of 65 percent was transported on the road (Jones, 2002). A reason for the transport of a large proportion of food products is because of the reliance of retailers on regional distribution centers. These centers are built adjacent to the roadways and therefore are the most efficient way to distribute food under the current scenario. A reworking of current distribution and travel logistics would therefore be needed in order to help facilitate the use of more efficient and greenhouse gas conservative methods of food transportation.

5. POSSIBLE SOLUTIONS AND FUTURE RESEARCH

5.1 Organic farms

Shifting to organic or smaller-scale organic farms is a possible solution for reducing CO_{2eq} emissions since they typically have fewer industrialized and mechanized processes, which leads to less fossil fuel inputs in the production of their produce. Compared to conventional agriculture, organic agriculture can reduce the energy use 20-

56% per crop dry matter unit when compared to the energy use in conventional agriculture, due to the decreased use of artificial fertilizers (Mader *et al.*, 2002). Organic beef and dairy production also have 40% and 15% less energy requirements, respectively, than do their conventional counterparts (Cederberg and Darelius, 2000). Refsgaard *et al.* (1998) also provides similar evidence for the energy benefits realized through conversion to organic farm operations, and shows that per unit of milk sold, organic farms use 19-35% less energy. Although the production of food is just one of many steps involved in the life of food, reductions in greenhouse gas emissions can be realized through a switch to organic agriculture.

5.2 Modifying Consumer Activities

Milá *et al.* (2008) made an important justification for including the consumer-food interaction in the analyses of the energy and greenhouse gas emissions from food products, by disclosing that 50% to 70% of the overall emissions for some food products is related to home processing, especially for energy use in cooking. These findings show that there is significant room for improvement of consumer-related emissions involved in the life cycle of food. One example is in the case of broccoli where the at-home preparation stage was responsible for 50-80% of the total energy used during the entire life cycle of the vegetable (Milá *et al.*, 2008). A different source calculated that about 20%, or 30.6 MJ, of energy used in the food chain is due to household activities, of which, 38.8% is due to cooking, 32.9% is due to washing-up, and 28.2% is due to cooling devices (Swedish Consumer Agency, 2003; Wallgren and Höjer, 2009). Researching more efficient cooking or cleaning methods, or using renewable energy sources could help reduce the total greenhouse emissions associated with food. For example, a microwave oven is up to ten times more efficient for baking potatoes than a conventional oven and an electric kettle is a more energy efficient way to boil water than is a hotplate (Wallgren and Höjer, 2009). Cooking several portions at once is also always more energy efficient than just cooking one portion.

There is also room for improvement in trade and commerce, especially with regards to buying and selling food on both large and small scales. According to Wallgren and Höjer (2009), the energy used during these two steps was responsible for 14% of the total energy used in some instances, 75% of which is attributable to trade and 25% of which is attributable to wholesale. The energy used for the transport of food in Sweden for example consists of 12% of the total energy used in the food supply system (Wallgren and Höjer, 2009). Comparatively, the energy used by private cars to shop for food is greater, consisting of about 40% of total energy used (Wallgren and Höjer, 2009). In this instance, efforts to improve the energy efficiency of private vehicles, such as hybrid or electric vehicles, would have a greater potential reduction in energy expenditures.

5.3 Shifting Consumer Diets

There are differences in the amount of energy that is needed to produce various types of food, with some products being more energy demanding and greenhouse gas intensive than others. Consider that raising animals through natural grazing for example uses about 5 MJ/kg of meat, whereas animals reared using concentrate feed or grain demands about 100 MJ/kg of meat (Wallgreen and Höjer, 2009). Weber and Matthews (2008) show that just minimal changes in diet, such as a 21-24 percent reduction in red meat consumption, can achieve greenhouse gas reductions similar to that of total localization of consumed food. Shifting just one day per week away from red meat and dairy to different proteins such as chicken or vegetable-based diets reduces greenhouse gas emissions by an amount equal to the same emissions released through driving between 1230 and 1860 km per year. A completely vegetable-based diet can reduce greenhouse gas emissions equivalent to driving 5340 mi/yr (8590 km/yr) or 8100 mi/yr (13 000 km/yr). Weber and Matthews (2008) also estimate that the climate impacts related to food for the average American household are approximately 8.1 tons of CO_{2eq} per year, with delivery food-miles only accounting for around 0.44 tons CO_{2eq} per year and total freight accounting for 0.9 tons CO_{2eq} per year. Improving diets is important as eating more vegetable-based or shifting away from eating red meat less than one time per week can have the same climate impact as buying all household food from local providers (Weber and Matthews, 2008).

6. CONCLUSIONS

In light of the information presented in the above sections regarding the variability and differences between different foods and their life cycles, it is apparent that there should be a shift away from solely focusing on reducing food-miles. Lack of homogeneity in the life cycle of food favors exploring the possibilities for improving the production, storage, and distribution processes involved. To reduce the contribution of production to greenhouse gas emissions, switching to organic agriculture could be a viable solution. Carrying out more wholesome and environmentally friendly farming practices such as intercropping, cover crops, biological pest management, and crop rotations are also an effective alternative to conventional agricultural practices. At this point in time however there is the need for improved organic agriculture study, as there is a lack of data on the global warming potential of different farming systems.

At the consumer-level, there is capacity for improving emissions efficiencies involved in the life cycle of food. Food preparation activities such as boiling, frying, or baking, use a relatively high amount of gas and electricity. This final stage alone can contribute a tremendous proportion of energy used in the life cycle of the food products. Improvements in energy efficiency in kitchen appliances or cooking methods could increase energy savings beyond those that would result due to sourcing food closer to home. Any improvements in the efficiency of household preparation and storage could lead to significant reductions in the greenhouse emissions associated with the life cycle of food as household electricity use for food can be as high as 22% for some homes (Statistics Sweden, 2009).

Consumers can help mitigate their contribution to the overall greenhouse gas emissions associated with the life cycle of food through actions such as avoiding trips for just one food item, going to closer stores, car-pooling to stores, becoming involved in a co-op local garden, having groceries delivered, and using more environmentally friendly means of transportation such as biking or hybrid vehicles. Modifying customer preference away from processed foods also could help reduce greenhouse gas emissions since these industrial steps usually require a great deal of energy-demanding packaging material. This warrants the need for future research in the potential role that customers can play in the reduction of greenhouse gas emissions involved with food.

Another improvement that could be made at the consumer level is in reducing food waste since greenhouse gases such as methane and CO_2 are released through the decomposition of food waste. Also, reductions in waste through improving the efficiency of production and processing of food could reduce emissions. The potential for future research into reducing food waste is needed as some studies show that upwards of one-third of food bought by consumers is thrown away (Wallgreen and Höjer, 2009). Future advancements in packaging and technology will play an important role in reducing food waste and maintaining food quality for longer periods of time.

Researchers should seek ways to improve efficiency of trade and commerce involved within the lifecycle of food. The majority of the energy used in these stages is due to the heating of commercial premises and for electricity used in lighting, refrigeration, and freezing of goods. As such, increasing the efficiency of buildings in order to reduce their requirements for heating, and using less electricity to cool food through technological innovations could allow for significant reductions in the energy needed by stores (Wallgren and Höjer, 2009)

To make for improvements in transportation, there should be investment in the advancement of technology, especially private cars used to shop for food. This is a small portion of the total distance travelled by food and yet still constitutes a disproportionately large amount of energy used. Future research on more sustainable modes of transportation such as hybrid or solar-powered technologies could help remediate some of the energy-associated emissions involved in food transportation.

At present, there is a lack of comprehensive data for gases such as methane and nitrous oxide. Information regarding these gases will allow for an improved comprehensive evaluation of the total greenhouse gas emissions involved in the life cycle of food. There are also inconsistencies with the scope used when defining the parts of the life cycle that will be considered in the analysis. Standardizing the scale used in the life cycle assessments of food could therefore allow for a better comparison of results between studies. Although there are certainly benefits to reducing food miles and eating locally such as stimulating the local economies, supporting local farmers, food security, and nutritional benefits, the food-miles argument is not a definitive reason for eating locally produced food.

Eating local is not always an option due to climatic variables. In cases such as these it is not logical from an energy standpoint to procure local foods as oftentimes more energy is spent in growing foods in ill-suited climates with innovations such as greenhouses. Additionally, in geographies where fresh produce cannot be grown year-round, prolonged storage and refrigeration of products may be implemented in order to provide fresh produce throughout the non-producing seasons. The act of refrigerating or freezing goods for prolonged periods of time can require a tremendous amount of energy, which once again can counteract the energy saved from sourcing foods that have travelled a shorter distance. Therefore, if there is a true regard for the improvement of the environment, there must be a call to action for the lessening of the emissions of greenhouse gases resulting from current production, storage, and distribution practices.

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