SUSTAINABLE AGRI-FOOD PRODUCTION AND CONSUMPTION

by

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Agri-food production is necessary to sustain the growing global population, but it adversely impacts the environment in various ways, including climate change, eutrophication, acidification, land and water uses, and loss of biodiversity, etc. These environmental impacts can also negatively affect human health, which could in theory outweigh the health benefits of nutritious food. While better agricultural practices need to be developed and applied to minimize the environmental burdens associated with the production chains, consumers are expected to implement more sustainable lifestyles and eat more environment-friendly foods. Life Cycle Assessment (LCA) is an analytical tool to evaluate the sustainability of a product by examining all the resources used and emissions generated during its life cycle. The first part of this work focused on the upstream production. An LCA of organic blueberry production was conducted to evaluate the trade-off between seasonal and local options and answer the question of whether imported fresh or domestic frozen blueberries are more sustainable. Fresh blueberries from Chile showed superior environmental performance within 2-week storage, due to lower electricity use associated with refrigeration and higher farming yield. Furthermore, length of storage and transportation distance were also found important; if farming yields are comparable, consumption of locally produced, fresh blueberries will be a better choice because of less energy use and shorter transportation distance. The second part of this work targeted at the downstream consumption and aimed to reduce the U.S. environmental footprint through changing adult eating habits. Supplemental functional units were applied in the LCA to incorporate the functions of food to provide nutrition and satiety. With controlled caloric intake, vegetarian diets were found overall more sustainable. However, large possible variations in the environmental impacts of the compared diets were observed due to wide range of nutritional quality of selected foods. Animal products, including meat and dairy especially, and discretionary foods were identified as hotspots in the American diet, that is, reducing the consumption of these foods or deliberately choosing

more sustainable alternatives within the same food categories, like chicken and low-fat milk, can significantly improve the sustainability of current American dietary patterns.

INTRODUCTION

Definition and scope of sustainability of agri-food systems

Sustainability is defined as the ability to meet the needs of the present generation without compromising the ability of future generations to meet their needs (World Commission on & Development, 1987). Sustainable agri-food production and consumption, therefore, should provide what the present human population needs while preserving, at global, regional, and local scales, the environments that are of habitable and sufficiently full of natural resources. Agri-food production sustains the global human population, but, along with other economic sectors, it also adversely impacts the environment in myriad ways, as summarized in Table 1. Due to the difference in farming practices, some foods have relatively higher footprint than others in terms of certain environmental impacts, such that a comprehensive examination on multiple impact categories is required to provide a complete picture of the environmental sustainability of agri-food production. Moreover, as specified in Table 1, some environmental impacts only apply to specific scales. Localized and regional impacts, such as acidification and eutrophication, can be particularly concerning to the well-being of the location that produces the commodity (Hudson & Hudson, 2004). Global warming, referring to a long-term rise in the average temperature of the earth's climate system, has received considerable research and policy attention due to its potential greater impacts.

The United Nations Intergovernmental Panel on Climate Change (IPCC) reports that widespread interventions are necessary to halt the rise in average planetary surface temperature to 1.5 ºC above pre-industrial levels (IPCC, 2018). If no action is taken, this temperature increase is on track to exceed 2 ºC, which will result in more severe damages. Some of the significant damages include changes in the climate system that result in more frequent and intensive precipitation at global scale, and drought in the Mediterranean region; vector-borne diseases; risks to coastal tourism such as heat extremes, storms, loss of beaches and coral reefs; hampered economic growth. Additionally, the impacts of agri-food production could have important bearing on human health, resulting from water availability/water stress threats, heatwave exposure, hydroclimate risk to power production, food crop yield reduction, and habitat degradation. Therefore, a slower rate of global temperature increase is urgently needed for all global species to better adapt to the increased temperatures.

Table I.1. Environmental impacts associated with agri-food production (Matthews, 2014)

Impact Category	**Scale**	**Contributing substances**
Global warming	Global	Carbon dioxide, nitrous oxide, methane, chlorofluorocarbons, hydrochlorofluorocarbons, methyl bromide
Stratospheric ozone depletion	Global	Chlorofluorocarbons, hydrochlorofluorocarbons, halons, methyl bromide
Acidification	Regional, Local	Sulfur oxides, nitrogen oxides, hydrochloric acid, ammonia
Eutrophication	Local	Phosphate, nitrogen oxide, nitrogen dioxide, nitrates, ammonia
Photochemical smog	Local	Non-methane hydrocarbon
Terrestrial toxicity	Local	Toxic chemicals with a reported lethal concentration to rodents
Aquatic toxicity	Local	Toxic chemicals with a reported lethal concentration to fish
Human health	Global, Regional, Local	Total emissions to air, water, and soil
Resource depletion	Global, Regional, Local	minerals used, fossil fuels used
Land use	Global, Regional, Local	Waste disposed in landfill or other land modifications
Water use	Regional, Local	Water used or consumed

Life cycle assessment

Life Cycle Assessment (LCA) is a tool that enables quantitative determination and comparison of the sustainability of industrial processes and products (European Commission, 2016). The LCA framework is standardized by the International Organization for Standardization in the ISO 14040 (ISO, 1997), including the following required steps: (1) Goal and scope; (2) Inventory analysis; (3) Impact assessment; (4) Interpretation, as shown in Figure 1. The rationale behind LCA is that processes and products have life cycles from “cradle-to-grave” or from the beginning to the end of use, and an accurate assessment of their sustainability requires analyses of all the inputs (materials, energy, natural resources), outputs (product, co-product, waste), emissions (air, water, land), and associated environmental impacts of each life cycle stage (Matthews, 2014). Application of LCA can promote the sustainability of agri-food production via: (1) Identifying problem stage and process (hotspot) in the production chain and prioritizing where to focus research and policy attention for improvement; (2) Evaluating typical dilemmas and tradeoffs faced by producers and consumers and facilitating comparison among different alternatives. A critical component of LCA is the functional unit (FU) concept, which is a quantitative basis for all the inputs and outputs to be related to the fulfillment of a specific function of the products. The LCA results of a product highly depends on the FU defined. To analyze the environmental impacts of a product (Table 1), the data on all its inputs and outputs within the boundary of the system focused needs to be collected, quantified and compiled.

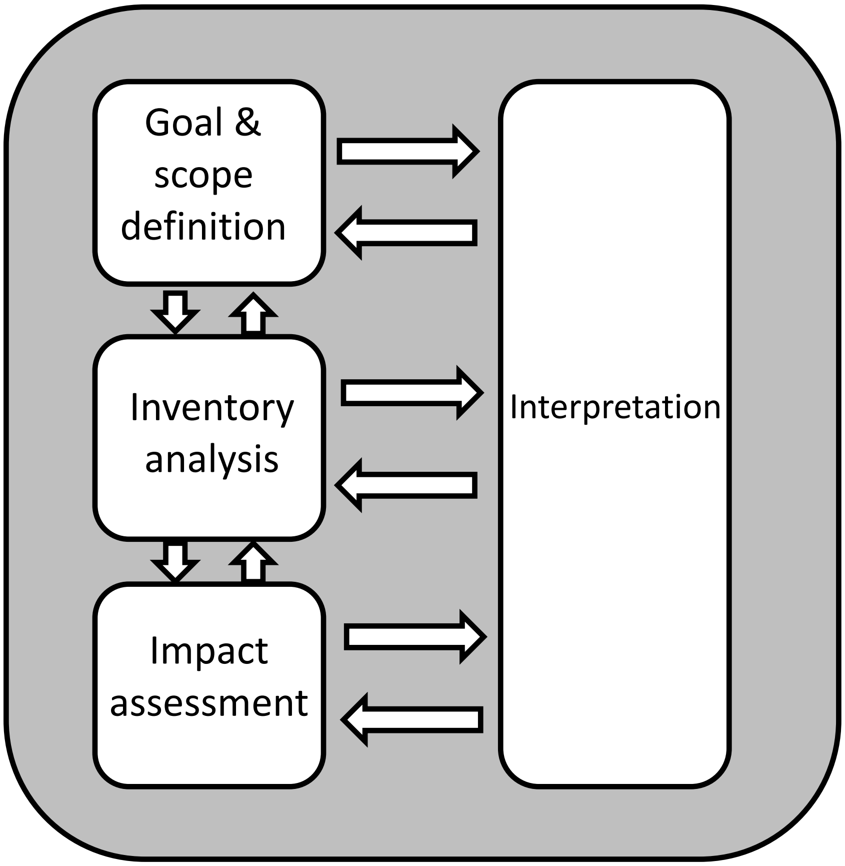

Figure I.1: Phases of an LCA

Objective and structure of the thesis

The U.S. is a major producer of agricultural goods on the global market and consumes more food energy per capita than any other country (FAOSTAT, 2019). The objective of the thesis is to evaluate the sustainability of the U.S. agri-food systems, covering upstream production and downstream consumption via life cycle approach, with an ultimate goal of helping U.S. farmers, food manufacturers, retailers and consumers reduce their environmental footprints. This thesis consists of two LCA case studies. The first study applied LCA to the organic blueberry production to evaluate the trade-off between seasonal and local options and answer the question of whether imported fresh or domestic frozen blueberries are more sustainable. The second study targeted at the downstream consumption and aimed to reduce environmental footprint of the U.S. adult population through dietary shifts. The main findings of this thesis and recommendations for future work are presented in the last chapter.

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PART 1.

A COMPARATIVE LIFE CYCLE ASSESSMENT OF FRESH IMPORTED AND FROZEN DOMESTIC ORGANIC BLUEBERRIES CONSUMED IN INDIANA

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Abstract

Blueberries are a crop with significant economic value and nutritional quality. Consumption of locally grown produce is generally considered more environmentally sustainable, but blueberries cannot be grown in all regions of the U.S. in all seasons. During the winter months, consumers in Indiana have the choice of purchasing domestically grown frozen blueberries or fresh blueberries imported from abroad, most commonly Chile. Although freezing uses more energy than refrigerating blueberries, the long transport distance between Chile and Indiana makes the consideration of which alternative is more sustainable a non-trivial question. Therefore, in this study, a comparative Life Cycle Assessment (LCA) was conducted to evaluate the environmental performance of Chilean fresh organic blueberries and frozen organic blueberries produced in two representative states in the U.S. This cradle-to-consumer LCA covered the farming and harvesting, processing, transportation, and storage stages. The farming and harvesting, postharvest processing, and transportation were identified as the environmental impact hotspots. The imported fresh blueberries were more sustainable than the domestic frozen blueberries in terms of acidification, global warming, ozone layer depletion, human toxicity, fresh water and marine aquatic ecotoxicity, and photochemical oxidation, as well as human health endpoint impact. Whether consumers should choose the frozen or fresh blueberries was found to be highly sensitive to the length of frozen storage and the type of refrigerant used.

Keywords: Life cycle assessment; Organic blueberry; Freezing; Refrigeration; Transportation; Storage

Highlights

- Life cycle impacts of Chilean fresh and U.S. frozen blueberries were compared.
- Farming and harvesting, processing, and transportation were hotspots.
- Michigan frozen blueberries generated the highest midpoint and endpoint impacts.
- For 2-week storage, Chilean fresh blueberries were overall the most sustainable.
- Results were highly sensitive to frozen storage period and refrigerant type.

1. Introduction

Blueberries are among the most popular fruits in the world and especially in high demand by health-conscious consumers due to their high concentration of anthocyanins, micronutrients, and dietary fiber (Evans, 2014). However, blueberries are highly perishable because of their high water content, which supports microbial growth and ongoing metabolic processes, especially respiration (Retamales, 2012). Therefore, cooling blueberries to 1 ºC within four hours of harvest is recommended to increase their shelf-life by up to eight to ten times, resulting from the reduction in respiratory rate. Alternatively, blueberries can be frozen, extending their shelf-life to a year or longer by reducing the rates of chemical reactions and microbial growth (De Ancos, Sánchez-Moreno, De Pascual-Teresa, & Cano, 2007).

The leading producers of blueberries in North America are the United States and Canada, and Chile is the largest producer in South America (Brazelton & Strik, 2007). While the U.S. is both the world's largest consumer as well as importer of blueberries, Chile is the leading exporter to the U.S. market (Evans, 2014). From 2011 to 2015, U.S. organic blueberry imports showed a steady growth, amounting to $8,399,000 in 2015. The major states for frozen blueberry production in the U.S. as of October 2015 included Washington, Oregon, Georgia, Michigan, California, North Carolina, and New Jersey, which produced 72, 49, 38, 31, 18, 11.7, and 6 million pounds, respectively (Payne, 2016).

Fruit production has generally been recognized as having both direct and indirect impacts on the environment. For example, mineral fertilizers used for conventional crops produce negative midpoint environmental impacts such as greater greenhouse gas (GHG) emissions and reduced water quality (Nesheim, et al., 2001). For the production of organic blueberries, their lower yields can result in higher land uses (Venkat, 2012) and larger amount of water required for irrigation (Ingrao et al., 2015). Additionally, the considerable amount of energy and refrigerants used to maintain the cold-chain results in significant GHG emissions that have global warming impacts (James & James, 2010). Since blueberries are grown in defined seasons, purchasing locally grown fresh blueberries is impossible in winter months. Therefore, year-round blueberry consumption raises further sustainability concerns since long transport distances have been proven to have significant negative environmental impacts by several studies (San Miguel et al., 2015).

Various studies have been conducted to determine the carbon footprint of blueberry farming (Bouzari, Holstege, & Barrett, 2015a) and compare conventional and organic blueberries production (Aguirre et al. 2012). However, very limited research has examined the environmental impacts of the entire life cycle of blueberry production. This study compared the production of U.S.-grown frozen and imported fresh blueberries using life cycle assessment (LCA) methodology. LCA is a widely recognized analytical approach to evaluate the environmental performance of industrial and agricultural processes and products (European Commission, 2016). To evaluate the potential environmental burden associated with a product during its life cycle, LCA is standardized in four steps: goal and scope definition, inventory analysis, impact assessment and interpretation (International Organization for Standarization , 2006).

The blueberry market is greatly influenced by the consumers. With more information regarding the environmental impacts resulting from producing, processing, transporting, and storing blueberries, consumers can make more informed decisions on the purchase of imported fresh or domestically produced frozen organic blueberries at supermarkets, especially when blueberries are out of season. This study primarily evaluated the environmental impacts associated with all the production stages of U.S.-grown frozen and imported fresh blueberries, including farming and harvesting, freeze processing, transportation into the state of Indiana, and subsequent retail storage and consumption. In this study, Washington and Michigan were chosen as the primary production and freeze processing sites because Washington has the highest frozen blueberry production and Michigan is a high producing state with close proximity to Indiana.

2. Methods

2.1 Goal and scope definition

The main goal of this cradle-to-consumer study was to identify the environmental impact hotspots in the blueberry supply chains so that sustainable practices can be recommended then adopted by blueberry producers. This study can also provide Midwestern consumers and retailers with information regarding the environmental impacts of purchasing or supplying freshly imported blueberries from Chile compared to U.S. produced, frozen blueberries shipped from Michigan and Washington to Indiana.

2.2 Functional unit

The functional unit was defined as 170 g of blueberries since this is a commonly sold weight of fresh blueberries packed in plastic clamshells of normal dimensions. Weight loss due to freezing and transpiration was not considered because these losses were assumed to be eliminated by optimal processes (Retamales, 2012). Fresh and frozen fruits are comparable with regards to nutritional quality according to the 2015-2020 Dietary Guidelines for Americans (Dietary Guidelines Advisory Committee et al., 2016), except for some micronutrients, such as ascorbic acid (< 570 μg/g) and phenolic compounds (< 27 mg GAE/g), which frozen blueberries showed higher values (Bouzari et al., 2015a) (Bouzari, Holstege, & Barrett, 2015b). Therefore, frozen and fresh blueberries were considered functionally equivalent in terms of equal weight in this study.

2.3 System boundaries

Figure 1.1 shows the system boundaries of this cradle-to-consumer study. After the farming and harvesting stages, the fresh blueberries system comprised packaging and cooling, refrigerated transportation from Chile to Indiana, refrigerated storage at retail, consumer transportation, and refrigerated home storage. In the frozen blueberries system, farming and harvesting were followed by freezing and packaging, frozen transportation from Washington and Michigan to Indiana, frozen storage at retail, consumer transportation, and frozen home storage.

2.4 Life cycle inventory (LCI)

The sources of the life cycle inventory data on the production of 170 g of fresh and frozen blueberries for all stages in the system boundaries studied are described below and summarized in Table 1.1.

2.4.1 Farming and harvesting

Farming and harvesting processes were determined following the practices in Chile for fresh blueberries, and the data was collected from Cordes et al. (2016), including agricultural factors such as land use, fossil fuels, compost, fertilizers (horn/bone meal, copper oxide), electricity, and machinery use. In the case of frozen blueberries from Michigan and Washington, the farming and harvesting inventory data was extracted from previous studies (Graeper & Bucien, 2011; Takele, Faber, Gaskell, Nigatu, & Sharabeen, 2007; Venkat, 2012), and manure was selected as the organic nitrogen source. The data on the water use for the Chilean, Michigan, and Washington blueberries production was collected from the Oregon State University extension service (2018). The annual production of organic blueberries in Chile was based on the mean yields reported by Cordes et al. (Cordes, Iriarte, & Villalobos, 2016), of 8,979 (± 2,350) kg/ha. The annual yields of organic blueberries in Michigan and Washington from 2014 to 2016, of 5242 (± 766) kg/ha and 10,827 (± 782) kg/ha, respectively, were collected from the governmental statistics and university extension fact sheets (US Department of Agriculture, 2015; US Department of Agriculture, 2016; US Department of Agriculture, 2017) with some modifications based on Venkat's (2012) assumption that yields of organic and conventional blueberries are equivalent (De Vetter et al., 2015). The variation in yield, of 26.17, 14.61, and 7.22% for Chile, Michigan, and Washington blueberries, respectively, was the main source of uncertainty of the calculated impacts. Other unit processes at later stages (e.g., processing, transportation, storage, as described below) are more standardized and can be well controlled, hence their contributions to the uncertainty of the values of impacts were assumed to be negligible in this study.

The uses of following materials during the farming stage were not considered due to small allocation based on mass: PE and PVC pipes for irrigation, PE film for frost protection, PE and PP films covering windrows for mulch, wood and wire.

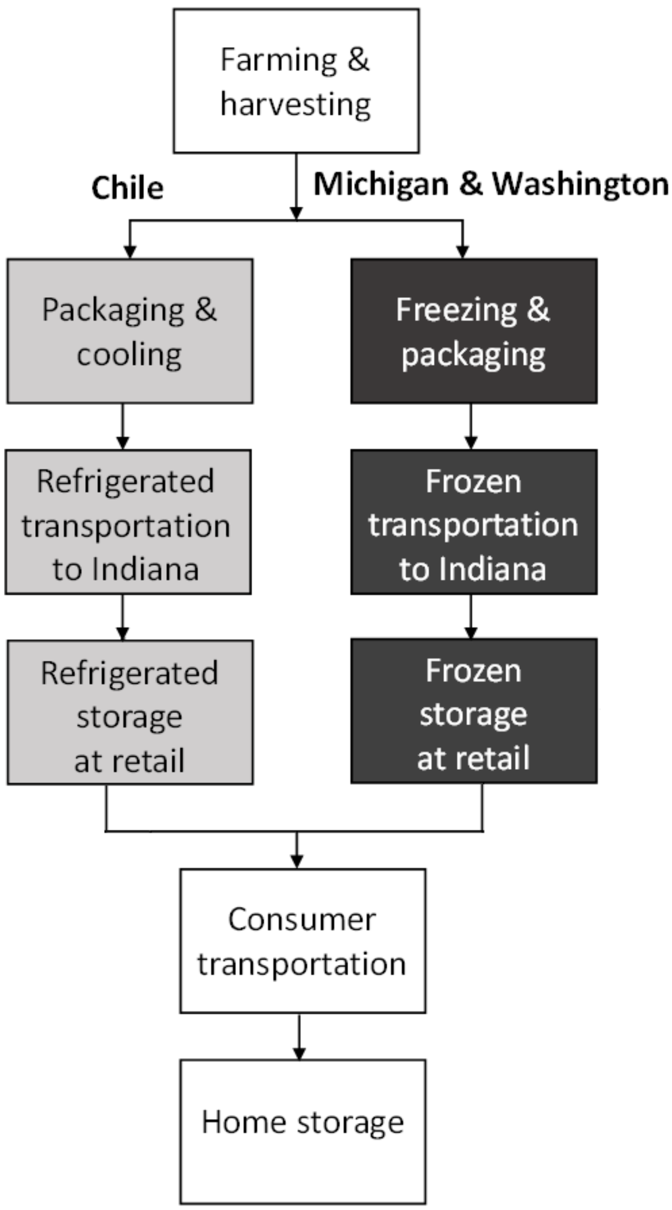


Figure 1.2. Process flow diagram of fresh and frozen blueberry life cycles.

2.4.2 Cooling/freezing and packaging

For fresh blueberries, polyethylene terephthalate (PET) clamshell containers were used for packaging. Data regarding the PET plastic was collected from the container manufacturer (Kheng, Ding, & Abdul Rahman, 2012). The weight and dimensions of the packaging were determined by primary measurements of the samples of North Bay Produce organic blueberries (Traverse City, Michigan, USA) purchased from a local Walmart supermarket in Indiana. Data on the electricity consumption of the cooling process was obtained from Thompson, Mejia, and Singh (2010), which presented the adjusted electricity use required to force air to cool blueberries from the intial temperature of 18 ºC to the final temperature of 0 ºC.

For frozen blueberries, data on the low-density polyethylene (LDPE) packages was analyzed and the package weight was measured using the samples of Great Value (Walmart) blueberries (340 g) purchased from a local Walmart supermarket in Indiana. Data regarding the material and energy uses for freezing and subsequent packaging processes was collected from Canals et al. (2008), which reported the aggregate data on a large produce freezing operation handling many different vegetable products. Aggregate data is considered more accurate than data on a single specific type of freezing process and product due to the large variety of freezing processes applied in frozen blueberry production, such as natural convection by air, forced convection by air, liquid immersion, contact, and cryogenic freezing (Sun, 2012). All the data regarding frozen blueberries was scaled by mass to fit the defined functional unit, *i.e.* 170 g of blueberries.

2.4.3 Transportation to Indiana

For fresh blueberries, the distance from Chile to the Midwest was estimated based on the information provided by an international freight shipping company (SeaRates, 2017), as 8,685 km between Valparaiso and Newark, New Jersey by ship and 1,172 km from Newark to Indiana by truck (total of a 22-day journey). The refrigerant data on the ocean freighter and diesel truck transportation was obtained from a worldwide refrigerant distributor (National Refrigerants, 2011) and Fitzgerald et al. (Fitzgerald, 2011), which presented that 19% of the total energy consumed during the sea journey is expended to maintain the refrigeration, while the remaining 81% is expended to physically transport the containers.

For frozen blueberries, the distances from Washington and Michigan to Indiana were obtained by estimation. The transportation from Washington to the Walmart Grocery Distribution Center in Indiana was estimated as 3,609 ± 163 km, based upon the mean distance between nine blueberry packers endorsed by the Washington Blueberry Commission (2017). The distance from Michigan to Indiana was 355 ± 99 km, as estimated using the mean distance of eleven endorsed packers from Michigan (Cultivate Michigan, 2017) to the Distribution Center in Indiana. These data, combined with the diesel truck outputs, was used to determine the contribution of transportation to environmental impacts.

2.4.4 Storage at retail

The data on storage at retail level was collected from Fricke et al. (Fricke & Becker, 2010), in which the electricity usage per square meter of storage/display area was 23.8 kWh/day for a supermarket open refrigerated display case, and 18.4 kWh/day for a closed-door freezer. Allocation of electricity usage to store 170 g of blueberries was calculated based upon the area that the blueberries occupy in the open refrigerated or closed freezing display units in the supermarket. Both fresh and frozen blueberries were assumed to be displayed for 1 week in the grocery store based on the shelf-life estimates for fresh blueberries (Almenar, Samsudin, Auras, Harte, & Rubino, 2008). While holding the storage time equal for fresh and frozen blueberries enabled a direct comparison of environmental impacts over the same period, a sensitivity analysis on the environmental burden associated with longer storage of frozen blueberries was conducted since it is well known that frozen blueberries can be stored for much longer periods. The use of refrigerants R22 was also considered in the sensitivity analysis. The refrigerant leakage rates were calculated using the data from the Container Handbook (Winfried, 2008), and an annual leakage rate of 15% of the total refrigerant charge was used.

2.4.5 Transportation from retail to household

The value of 6.8 km was used as the average distance from supermarket to home in the Midwest (Fettig, 2006). Inventory data regarding common passenger vehicle was obtained from the National Renewable Energy Laboratory (NREL) database (2017). Mass allocation of the environmental impacts was based upon the ton-km required to transport 170 g of blueberries for 6.8 km.

2.4.6 Household storage

The data on blueberry storage at household level was obtained from an energy efficiency utility, Efficiency Vermont (2017). Electricity usage was based on the total of 1.88 kWh/day for a 14 cubic foot home combined refrigeration/freezing unit. The electricity allocated to the storage of 170 g of blueberries was calculated using the area occupied by the measured package dimensions in the refrigeration/freezing unit, which equaled 0.0028 kWh/day. R22 was compared as an alternative refrigerant, and its leakage rates were calculated using the data from the Container Handbook (Winfried, 2008).

2.5 Impact assessments

The midpoint environmental impacts associated with the production of fresh and frozen blueberries estimated in this study included abiotic resource depletion (kg Sb equivalents), acidification potential (kg SO_2 equivalents), eutrophication potential (kg PO_4 equivalents), global warming potential (GWP, for 100-year time horizon, kg CO_2 equivalents), stratospheric ozone depletion potential (kg CFC-11 equivalents), human toxicity potentials, freshwater and marine aquatic ecotoxicity (kg 1,4-DB equivalents), and photochemical oxidation (kg C_2H_4 equivalents). The CML 2 Baseline 2000 method was used to calculate all the midpoint impacts, except the emissions resulting from refrigerant uses and passenger vehicle, which were calculated using the TRACI method. The endpoint human health impact in terms of Disability Adjusted Life Year (DALY) was calculated using the Eco-indicator 99 (Egalitarian) method v2.05. All the calculations were performed in SimaPro 7.1 software (PRé Consultants, Netherlands).

2.6 Statistical analysis

The values of the calculated environmental impacts were subjected to one way analysis of variance (ANOVA) followed by the post hoc Duncan's test using SAS 9.1 (SAS Institute, Cary, USA). Significant differences were declared at a probability level $p<0.05$.

3. Results and Discussion

3.1 Inventory analysis

Table 1.1 shows the global inventory data about the production systems of 170 g of fresh and frozen blueberries. Farming and harvesting inputs were determined based on the average yield in each region. The frozen blueberries grown in Michigan consumed more resources than those in Washington due to the lower productivity. Although the Chilean blueberries used 4.1 and 3.5 times more diesel and electricity, respectively, than the Michigan ones, they required much less compost, manure, and refinery gas (5.6−28.6 times) than the Washington ones.

At the postharvest stage, the freezing process utilized almost 8 times more electricity than cooling for blueberries, as expected. The frozen transportation of Michigan blueberries by diesel truck required less energy than the refrigerated transportation of fresh blueberries from Newark, New Jersey after being imported from Chile. In addition to the effect of distance difference, temperature fluctuations during frozen transportation are considered insignificant, especially when the storage temperature is below −10 ºC. At this temperature the fluctuation is within a tolerance of ± 0.2ºC, and the compressor and fans of the freezing system are generally off, resulting in energy savings. In contrast, in the case of refrigerated transportation, the compressor and fans run at full capacity during the entire trip (Morawicki, 2012). Specific ambient conditions, quality of insulation, and journey conditions such as vibrations also influence the energy consumption during transportation. Furthermore, the transportation of fresh blueberries utilized a larger amount of refrigerant, which was 13 and 134 times more than those consumed by transporting frozen blueberries from Washington and Michigan, respectively.

At the retail stage, displaying fresh blueberries in the open refrigerated cases consumed nearly 4 times more electricity than storing frozen blueberries in the closed-door freezers. Lindberg et al. (2008) conducted field-measurements on energy efficiency of vertical display cabinets in a Swedish supermarket, and also found reductions in electrical supply to the cabinets by 26% following the installation of glass doors.

Table 1.1. Life cycle inventory (per 170 g) of fresh and frozen blueberry production

Farming & Harvesting				
Input	**Chile**	**Michigan**	**Washington**	**Unit**
Land use (100% occupied)	2.10×10^{-1}	3.32×10^{-1}	1.58×10^{-1}	m^2
Water	1.15×10^{2}	2.02×10^{2}	9.62×10^{1}	l
Diesel	4.02×10^{-3}	9.76×10^{-4}	4.64×10^{-4}	kg

Table 1.1 continued

Compost	1.46×10^{-2}	1.70×10^{-1}	8.10×10^{-2}	kg
Horn/bone meal	--	4.90×10^{-3}	2.33×10^{-3}	kg
Manure	5.68×10^{-3}	2.45×10^{-1}	1.16×10^{-1}	kg
Copper oxide	7.32×10^{-4}	--	--	kg
Refinery gas	1.93×10^{-4}	1.17×10^{-2}	5.55×10^{-3}	kg
Electricity	1.08×10^{-1}	3.05×10^{-2}	1.45×10^{-2}	kWh
	Packaging & Cooling	**Freezing & Packaging**		
PET	1.50×10^{1}	--	--	g
LDPE	--	1.05×10^{1}	1.05×10^{1}	g
Diesel	--	5.46×10^{-5}	5.46×10^{-5}	kg
Corrugated cardboard	--	7.75	7.75	g
Waste water	--	3.71	3.71	l
Electricity	5.9×10^{-3}	4.52×10^{-2}	4.52×10^{-2}	kWh
Transportation to Retail				
Ocean freighter	1.03	--	--	tkm
Diesel truck	1.51×10^{-2}	8.54×10^{-3}	8.68×10^{-2}	tkm
Ammonia	1.12×10^{-4}	8.34×10^{-7}	8.48×10^{-6}	kg
Storage at Retail				
Electricity	1.96×10^{-2}	5.09×10^{-3}	5.09×10^{-3}	kWh
Ammonia	2.83×10^{-5}	2.83×10^{-5}	2.83×10^{-5}	kg
Consumer Transportation				
Consumer car	1.35×10^{-3}	1.35×10^{-3}	1.35×10^{-3}	tkm
Home Storage (for 7 days)				
Electricity	1.96×10^{-2}	1.96×10^{-2}	1.96×10^{-2}	kWh
Ammonia	2.79×10^{-5}	2.79×10^{-5}	2.79×10^{-5}	kg

3.2 Midpoint impact assessment

Table 1.2 shows the total midpoint impacts resulting from the production of 170 g of blueberry in Chile, Michigan, and Washington. Michigan frozen blueberries generated the highest impacts ($p<0.05$) in all the categories studied, which was mainly because of their lowest yield. Fruit productivity depends on agronomic management and environmental factors such as crop management, plant physiology and variety, soil quality, occurrence of frost, amount of sunshine, rain, and other weather events (St. Pierre, 2006). Since many of these factors cannot be controlled by human activity, they can cause a high level of uncertainty directly affecting the results of impact assessment.

The fresh blueberries from Chile appeared to be more environmentally friendly in terms of acidification, global warming, ozone layer depletion, human toxicity, fresh water and marine aquatic ecotoxicity, and photochemical oxidation, which can be attributed to the less amount of refrigerant used.

Figure 1.2 shows the contributions of different life cycle stages of the fresh and frozen blueberry systems to the midpoint environmental impacts. Farming/harvesting and processing were the two major contributors to abiotic (resource) depletion, totally accounting for over 74.6, 91.2, and 81.3% for Chile, Michigan, and Washington, respectively. Transportation was the next most important stage for Chile and Washington but contributed little to abiotic depletion for Michigan due to the significantly shorter transport distance. The acidification potential of frozen blueberries was similarly dominated by the farming/harvesting and processing, however, the fresh blueberries showed a more even pattern in which no single stage took up more than 30%. For eutrophication potential, farming and harvesting was the hotspot in the frozen blueberry production, and processing and transportation took the lead for fresh blueberries.

Table 1.2. Midpoint impacts of 170 g of Chilean, Michigan, and Washington blueberries

Impact category	**Unit**	**Chile**	**Michigan**	**Washington**
Abiotic depletion	10^{-3} kg Sb eq.	1.34±0.17[a]	1.53±0.11[a]	1.30±0.02[a]
Acidification	10^{-3} kg SO_2 eq.	1.00±0.07[c]	1.53±0.11[a]	1.34±0.02[b]
Eutrophication	10^{-4} kg PO_4 eq.	1.46±0.04[a]	1.65±0.17[a]	1.38±0.03[a]
Global warming	10^{-1} kg CO_2 eq.	1.50±0.21[b]	2.93±0.32[a]	2.04±0.07[b]
Ozone layer depletion	10^{-8} kg CFC-11 eq.	2.87±0.24[c]	15.8±1.18[a]	12.4±0.09[b]
Human toxicity	10^{-1} kg 1,4-DB eq.	1.02±0.07[b]	235±0.04[a]	235±0.006[a]
Fresh water aquatic EcoTox.	10^{-2} kg 1,4-DB eq.	1.12±0.17[b]	232±0.09[a]	231±0.01[a]
Marine aquatic EcoTox.	10 kg 1,4-DB eq.	25.9±4.43[b]	40.4±2.43[a]	32.9±0.31[ab]
Terrestrial ecotoxicity	10^{-4} kg 1,4-DB eq.	7.09±0.29[b]	8.33±0.60[a]	6.34±0.12[b]
Photochemical oxidation	10^{-5} kg C_2H_4	3.32±0.29[b]	8.54±0.42[a]	7.90±0.08[a]

Results with different letter are significantly different (p<0.05).

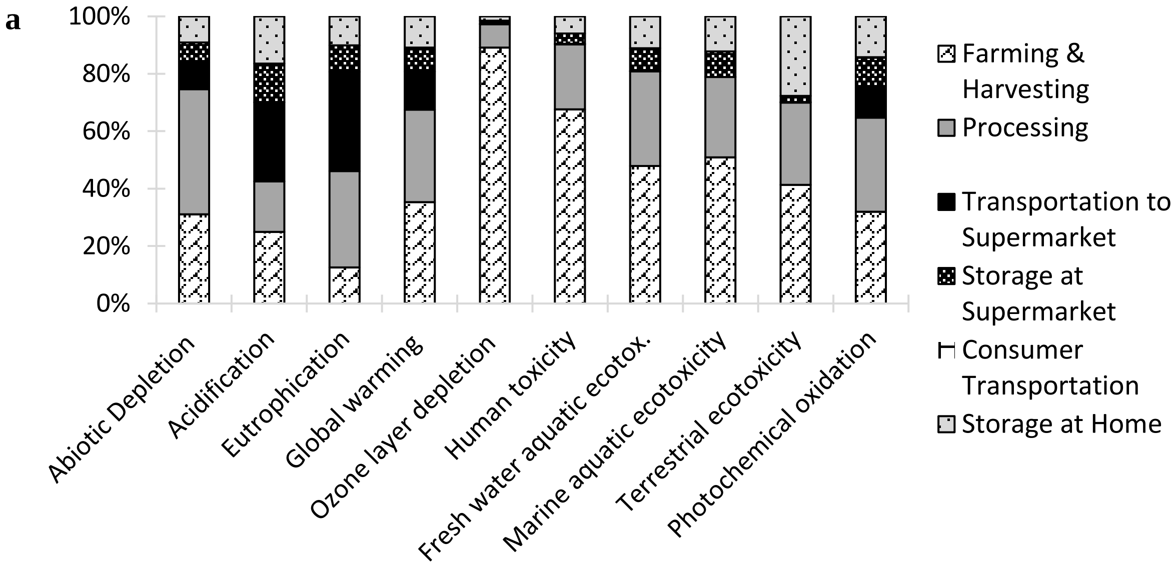
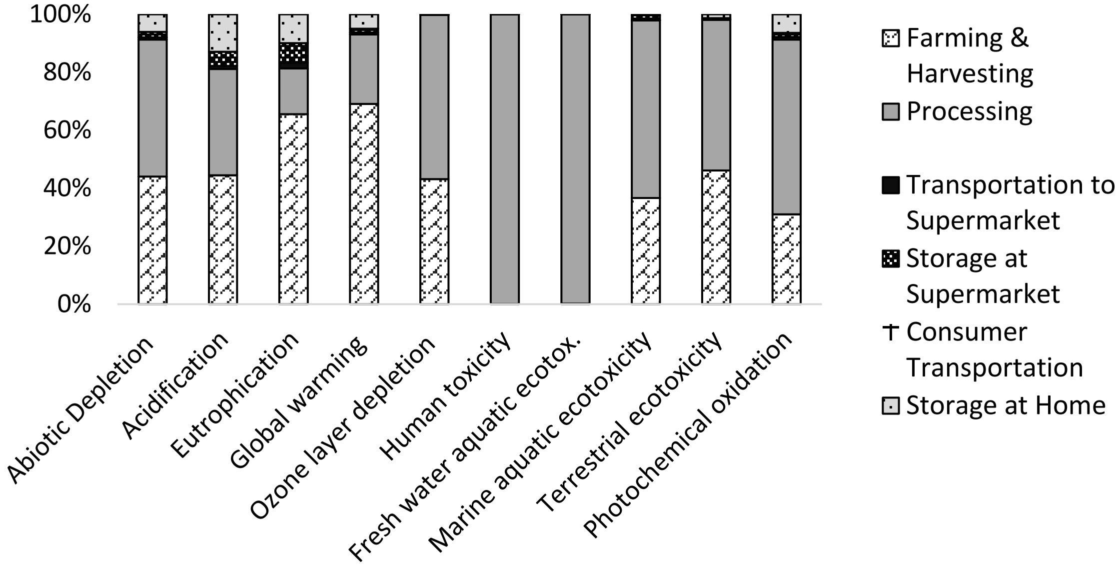


Figure 1.2. Midpoint impacts of different life cycle stages of blueberry production in (a) Chile, (b) Michigan and (c) Washington.

Figure 1.2 Continued

b



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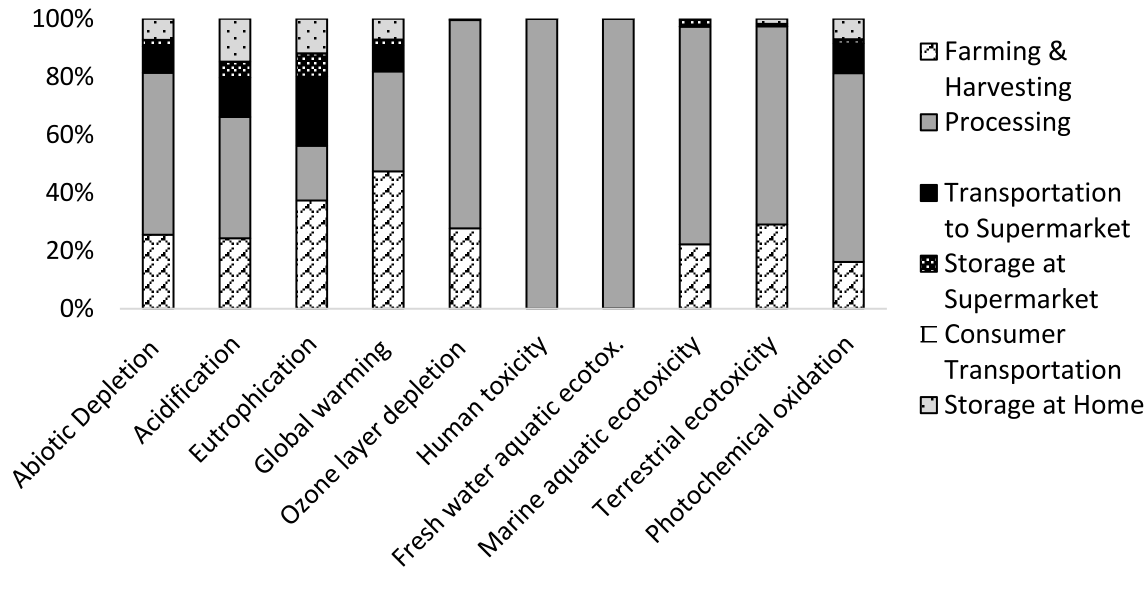

For global warming, farming and harvesting was the most important stage for Michigan and Washington, accounting for 69 and 47% of the life cycle GWP, respectively. This impact was derived from the utilization of diesel fuel on farms as well as electricity usage generated mainly by fossil fuel. The second most important stage for Washington was freezing and packaging, of

34%, which was followed by transportation, of 9%. However, in the case of Michigan, since transport distance was much shorter, the energy-intensive freezing and packaging processes were responsible for 24% of the GWP, while transportation took up only less than 1%. Chilean blueberry production presented a relatively even distribution of GWP along its life cycle, in the order of farming and harvesting, processing, and transportation, with 35, 32, and 13% of the total value, respectively. Although Chilean blueberries had the longest transport distance, the majority of this journey was via ocean freighter, which emitted less GHG per ton-km of blueberries transported than semi-trailer trucks due to mass allocation.

Ozone layer depletion, human toxicity, fresh water and marine aquatic ecotoxicity, terrestrial ecotoxicity and photochemical oxidation showed similar patterns in the Chilean system, with farming and harvesting as the most important stage followed by processing. However, processing was the single key contributor to ozone layer depletion, marine aquatic and terrestrial ecotoxicity, and photochemical oxidation for frozen blueberries, especially in the Washington system, accounting for 73, 99, 99 and 75%, respectively. Processing was also the dominating stage (>99%) of human and freshwater toxicity associated with frozen blueberries. These results suggest that the refrigerant use for postharvest freezing and frozen transportation was the hotspot of ozone depletion, human and freshwater toxicity due to its high ozone depletion potential and emissions to air and water (Benhadid-Dib & Benzaoui, 2012). Furthermore, the use of LDPE plastic packaging for frozen blueberries may also cause toxicity to both human and environment due to the consumption of primary resources (e.g., natural gas and crude oil) for its production and the associated emissions to air (e.g., CO_2, NO, SO_2, and aromatic hydrocarbons). Polymer packaging has been reported to cause impacts on resource use, climate change, human health, and ecosystem quality (Siracusa, et al., 2014). Overall, the most significant differences in the environmental profiles resulting from different blueberry life cycles were ozone layer depletion, human toxicity and fresh water aquatic ecotoxicity.

3.3 Endpoint impact assessment

Figure 1.3 shows the human health impact expressed in DALY associated with the production of fresh and frozen blueberries in different regions. Despite long transport distance, the fresh blueberries from Chile were a healthier option from both the environmental and human health perspectives mainly because of the relatively energy-saving cooling process compared to freezing at the postharvest stage. For the frozen blueberries, although Michigan had a shorter transport distance compared to other regions, its lower blueberry productivity generated a 2-fold higher impact than Chile and Washington systems at farming and harvesting stage. Long distance transportation was found to contribute to respiratory organics and inorganics (data not reported). Transporting Washington blueberries to Indiana accounted for 25% of the DALY value, which was slightly higher than the transportation from Chile, but was 10 times of the Michigan case. Therefore, there was no significant difference ($p>0.05$) between the overall DALY values of Michigan and Washington blueberries. On the other hand, processing of frozen blueberries contributed approximately 34% of total DALY, which was 1.7 times higher than that of fresh blueberries. Processing was the main contributor to all the human health impact categories except carcinogens, which were dominated by farming and harvesting (data not reported).

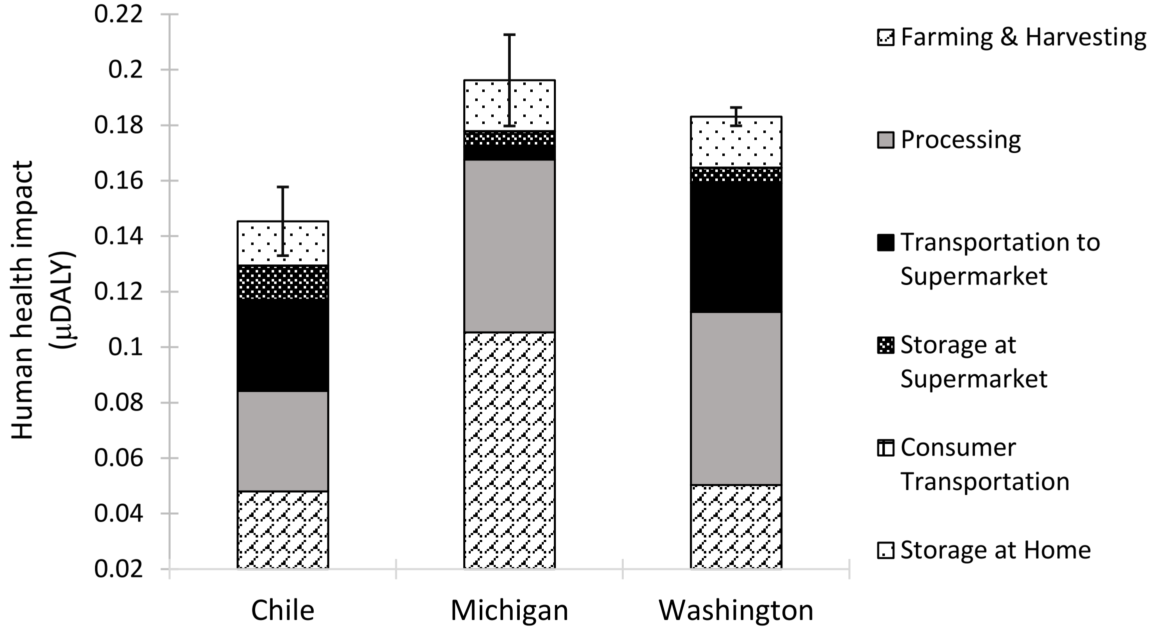

Figure 1.3. Overall human health impact (per 170 g) of fresh and frozen blueberries.

3.4 Sensitivity analysis

Because the shelf-life of fresh blueberries is approximately 2 weeks (Almenar et al., 2008), all the results presented above were based on the assumption that the fresh and frozen blueberries were stored for an equivalent period of 1 week in supermarket and 1 week at home. However, due to the reduced availability of water (George, 1993), the frozen blueberries from Washington and Michigan in fact can be stored for a much longer period and consumed out of season, when domestically produced fresh blueberries are generally unavailable. Since the shelf-life of frozen blueberries is normally up to 12 months, it is reasonable to assume that the total period of storage (i.e. retail and household) of frozen blueberries can in reality be several months longer than two weeks (Kramer, 1982).

According to the results of midpoint impact assessment (Figure 1.2), blueberry storage played an important role in eutrophication, contributing over 16% regardless of system. Figure 1.4 shows the effect of extended frozen storage on the overall eutrophication potential associated with three systems. The eutrophication potential increased with storage period, as expected, which can be attributed to the increasing ammonia usage, resulting in higher nitrogen emissions (Payen & Ledgard, 2017). The blueberries from Michigan produced a higher GWP than those from Chile and Washington regardless of storage period. On the other hand, the Washington system showed a lower eutrophication potential than the Chile system when the blueberries were stored for 2 weeks. However, the eutrophication potential of Washington blueberries would become higher than that of Chilean ones if the frozen storage was extended to longer than approximately 4 extra days.

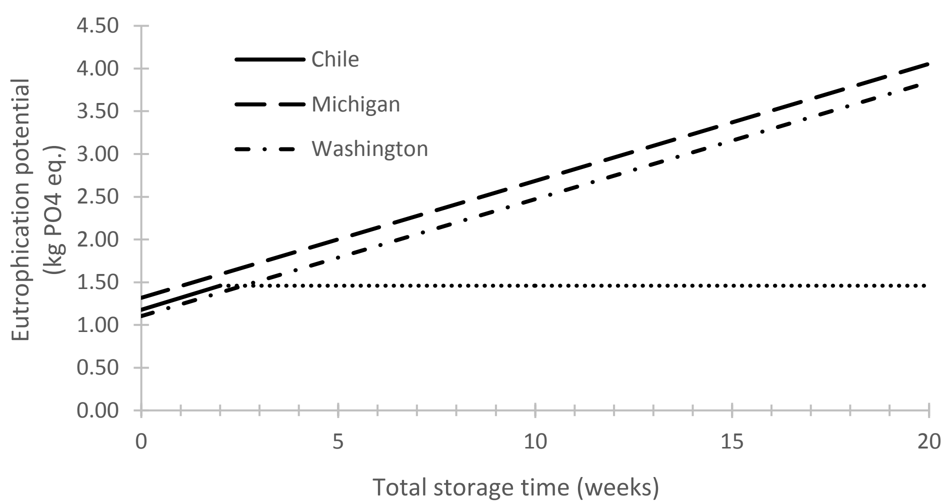

Figure 1.4 The effect of storage period on the eutrophication potential associated with blueberry production in different regions. Horizontal dashed line serves as guide of the eye, indicating the value of Chilean blueberries stored for 2 weeks.

In addition to eutrophication, refrigerant uses for both storage and transportation were found to be one of the major contributors to acidification, global warming and ozone layer depletion associated with the life cycle of blueberries. The effect of refrigerant type on the midpoint impacts was also analyzed and shown in Table 1.3. The results indicated that if storage and transport refrigerant was changed from ammonia (NH_3) to hydro-chlorofluorocarbon (HCFC) refrigerant such as R22, the acidification and eutrophication potentials would slightly decrease by 8−13% for fresh blueberries and by 5−14% for frozen blueberries. In contrast, the GWP and ozone depletion would increase by approximately 1.6 times and up to 19−24 times, respectively. While R22 accounts for 3.9% of the refrigerants used in the U.S. in 2018, it will become officially phased-out by 2020 as being declared by the U.S. Environmental Protection Agency (EPA; 2017). Results in Table 1.3 reaffirmed the disproportionately high ozone layer depletion impact of R22 and the importance of its replacement.

Table 1.3. Effect of refrigerant type on midpoint impacts associated with blueberry production in different regions

Impact	**Unit**	**Chile**		**Michigan**		**Washington**	
		NH_3	R22	NH_3	R22	NH_3	R22
Acidification	10^{-4} kg SO_2 eq.	10.0 ±0.7[a]	9.12 ±0.6[a]	14.6 ±1.6[a]	13.8 ±1.6[a]	13.4 ±0.2[a]	12.5 ±0.2[a]
Eutrophication	10^{-4} kg PO_4 eq	1.46 ±0.04[a]	1.26 ±0.05[a]	1.59 ±0.2[a]	1.41 ±0.2[a]	1.38 ±0.03[a]	1.19 ±0.03[a]
Global warming	10^{-1} kg CO_2 eq.	1.50 ±0.2[b]	2.51 ±0.2[a]	2.88 ±0.3[b]	3.90 ±0.3[a]	2.04 ±0.07[b]	3.06 ±0.07[a]
Ozone layer depletion	10^{-8} kg CFC-11 eq.	2.87 ±0.2[b]	284 ±0.2[a]	15.8 ±1.2[b]	297 ±1.2[a]	12.4 ±0.09[b]	293 ±0.09[a]

Results with different letter are significantly different ($p<0.05$).

4. Conclusions

This cradle-to-consumer life cycle assessment compared the environmental profiles of fresh organic blueberries imported from Chile with frozen organic blueberries grown in Washington and Michigan. The midpoint and endpoint impact assessments identified the hotspots of environmental and health impacts, which include farming and harvesting, energy use for freezing and packaging operations, and long transport distances. Despite of the shortest transport distance, the lower productivity caused Michigan blueberries to generate the highest midpoint and human health endpoint impacts, while the blueberries from Chile were found to be the most sustainable option when the storage periods were held equal for two weeks.

While fresh blueberry packages usually list the country and state of origin, frozen blueberry packages are typically marked only with country of origin. For consumers, the answer to the question of whether domestic frozen blueberries are more sustainable than imported fresh blueberries during out-of-season times has been found to be highly sensitive to how long the frozen blueberries are stored in supermarket and at home. The sensitivity analysis showed that the consumption of frozen blueberries grown in Washington is likely more sustainable than the consumption of Chilean fresh blueberries if they are stored for less than 2.6 weeks.

Due to the differences in species, climate and soil conditions, and farming practices, the variation in blueberry productivity significantly affected the amount of resources required at the farming and harvesting stage, which was the main source of uncertainty of this work. Therefore, the calculated impacts associated with this stage might not represent all conditions, and their extrapolation to other geographic areas could be less accurate. Since transportation depends on the region as well, our research provides a framework that can be applied to future studies on organic blueberries or other fruits in multiple regions, which can better help understand the region-to-region variations. In contrast, other unit processes included in this study (i.e., packaging, refrigeration, freezing, transportation, storage) are more standardized and can be well controlled, hence their data are more generalizable to LCA studies on other fruits.

Eating local and fresh food is encouraged to benefit food system sustainability. However, most of fresh produce like cherry, asparagus, etc. are seasonal, hence transportation from other regions or postharvest processing (e.g., drying, canning, freezing) for long-term storage are alternatives for out-of-season consumption. This research can be implied as practical guidelines to evaluate the environmental tradeoffs between imported fresh and local processed fruits and vegetables when local fresh options are not available. The results will help consumers and retailers understand the associated impacts, and thus make more informative decisions on choosing environment-friendly fruits and vegetables.

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PART II

EVALUATION OF ENVIRONMENTAL PERFORMANCE OF AMERICAN DIETARY PATTERNS CONSIDERING FOOD NUTRITION AND SATIETY

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Abstract

The effect of food choice for the daily diet of adults in the U.S. on its environmental performance was evaluated via a comparative life cycle assessment (LCA) of the "typical" dietary pattern and those recommended by the U.S. Dietary Guidelines, including "healthy", Mediterranean and vegetarian. Supplemental LCA functional units (FUs) were applied to incorporate the functions of food to provide nutrition and satiety, namely Nutrient Rich Foods Index 9.3 (NRF9.3), Nutritional Quality Index (NQI), and Fullness Factor™ (FF). Life cycle inventory data was collected for 14 food categories consisting of 80 component foods, and their midpoint environmental impacts including global warming, terrestrial acidification, and freshwater eutrophication potentials were calculated. Diets in accordance with each pattern were constructed from selected component foods and normalized to 2000 kcal. Vegetarian diets were found to produce the lowest carbon footprint regardless of the FU. However, high possible variations in the environmental profiles of the compared diets were identified due to the wide range of food choices, which showed highly different nutrition and satiety scores even within the same food category. Animal products, including meat and dairy especially, and discretionary foods were identified as the hotpots of global warming and terrestrial acidification, and refined grains were the main contributor to freshwater eutrophication. Discretionary foods consistently exhibited higher impacts on the basis of nutritional FUs due to their low nutrient density. The results can be implied as practical guidelines to help reduce the environmental footprint associated with current U.S. diets without compromising their nutritional adequacy and satiety.

Keywords: *Dietary pattern; Nutrition; Satiety; Functional unit; Sustainability; Life cycle assessment*

Highlights:

- Dietary environmental profile depends on nutrition and satiety of component foods
- Foods even within same category show a large variation in environmental footprint
- Vegetarian diets can be nutritious and more environment-friendly
- Meat, poultry and eggs, dairy and discretionary foods are hotspots in U.S. diets

1. Introduction

The world faces an expanding human population that is projected to increase to 9.2 billion by the year 2050 (Ansari, 2011). To satisfy the increasing demand for food, agriculture continues to become more intensive, which, however, significantly causes increased environmental burdens due to human activities and land use (Tilman, Balzer, Hill, & Befort, 2011). The agriculture sector contributes a large share of climate change because of an estimated one-third of global greenhouse gas (GHG) emissions (Sonesson, Davis, Hallstrom, & Woodhouse, 2019). Agricultural production also involves considerable water use and plays an important role in eutrophication and acidification of water supplies (Ansari, 2011).

Food is an essential element of human health, but in the developing world there are approximately 10% of the global population in malnutrition and hunger, who consume too little energy and insufficient nutrients. On the contrary, in the developed countries there is a large population malnourished and obese due to excessive intake of nutritionally poor foods (I. FAO, UNICEF, WFP, and WHO, 2018). For example, the obesity epidemic and rise in chronic diseases currently faced by the U.S. has been widely attributed to the overconsumption of low nutrient density and high energy foods (Doran-Browne, Eckard, Behrendt, & Kingwell, 2015; Imamura et al., 2015). Given these challenges, sustainable food production and consumption, in terms of minimizing global environmental burdens while maximizing human health is under growing attention (Gilly, Danielle, Brad, Michalis, & Manny, 2016; Hallström, Davis, Woodhouse, & Sonesson, 2018; Sonesson et al., 2016).

The typical dietary pattern of developed countries may increase the medical costs associated with poor public health (e.g., obesity and chronic disease) (WHO, 2013), and also adversely impact the environment. Defining and adopting healthier and more environmentally sustainable dietary patterns have become a growing research field. A meta-analysis of twelve literature studies reported that reducing the portion of animal-source food in a diet can improve both its nutritional quality and associated carbon footprint (Van Kernebeek, Oosting, Feskens, Gerber, & De Boer, 2014). Reducing consumption of red and processed meat in an UK dietary context was found to enable a 35% reduction in GHG emissions (Hoolohan, Berners-Lee, McKinstry-West, & Hewitt, 2013). However, an opposite correlation between the nutritional and environmental performance of dietary trends has been reported in several studies. Vieux et al, found that in a French context, diets with higher nutritional quality had significantly higher GHG emissions (Vieux, Soler, Touazi, & Darmon, 2013). Perignon et al also studied French dietary patterns and found the carbon footprint of a diet could not be reduced by more than 30% without compromising its nutritional quality (Perignon et al., 2016). While the effect of eating habit on the sustainability of agricultural systems has been widely investigated in European countries, the associated knowledge of the U.S., the country with the highest per capita food consumption in the world on the energy basis, is still limited.

Life cycle assessment (LCA) is an analytical tool to evaluate the environmental performance of agricultural systems and products (EC, 2013). While LCA has been widely performed on a variety of foods (Andersson, 2000; de Vries & de Boer, 2010; Notarnicola, 2015; Y. Wang, Thoma, Kim, & Burek, 2016), most food LCA studies calculated their environmental impacts based on mass or volume as the functional unit (FU). However, the functions of food are complex, in which delivery of energy and specific nutrients is considered the most important (Hallström et al., 2018; Sonesson et al., 2019). There is hence a need for a more appropriate FU for food LCA that better incorporates food nutritional quality (Masset, Vieux, & Darmon, 2015). When a nutritionally based FU is employed in LCA, the environmental performance of diets depends on the individual food items included, and their combination that are typically consumed together (U. Sonesson et al., 2019). In the U.S., to fulfill the nutritional requirements, healthy eating habits are generally recommended following the Dietary Guidelines for Americans (*2015-2020 Dietary Guidelines for Americans*, 2015). Another primary function of food that is important to nutrition scientists but has received little attention in food LCA is to provide satiety. Satiety, or the feeling of fullness that accompanies a meal, can inhibit sensations of hunger and consequently reduce total caloric intake (Chambers, McCrickerd, & Yeomans, 2015). High satiety foods hence have the potential to reduce total food consumption. However, to the authors' best knowledge, no particular investigation has been carried out on the correlation between satiety and environmental performance of daily diets.

Since a sustainable diet can be defined as "nutritionally adequate, safe and healthy; while optimizing natural and human resources" (FAO, 2010), the health benefits of the eating patterns of a society should be remeasured considering the environmental impacts associated with a food's life cycle. The aim of this work was to offer quantitative insights into the environmental implications of dietary choice by applying, in addition to a mass-based FU, three different FUs defined based on nutrient and satiety indices to integrate nutrition aspect into LCA. This LCA study comprehensively examined the environmental profiles of four different U.S. diet scenarios which included eighty food items. The results will help the U.S. public better understand the environmental performance of their current diets from new perspectives and take action to develop more sustainable eating habits.

2. Methodologies

2.1 Functional units of life cycle assessment

One of the objectives of this work was to develop and apply a new FU that captures the satiety function of food in the U.S. dietary context, and evaluate its usability by comparing to three different FUs. The mass-based FU was defined as the mass of food in a diet which provides 2000 kcal. Two FUs related to nutrient quality were defined based on Nutrient Rich Foods Index 9.3 (NRF9.3) and Nutrient Quality Index (NQI).

The NRF9.3 was originally developed by Drewnoski et al., and is based on nine qualifying nutrients encouraged to consume in diet and three disqualifying nutrients discouraged (Drewnowski, 2009).

$$\text{NRF9.3} = \sum_{i=1}^{i=9}\left(\frac{x_i}{RDV_i}\right) - \sum_{j=1}^{j=3}\left(\frac{y_j}{MRV_j}\right) \qquad (1)$$

where
i (qualifying nutrients): protein, fiber, vit. A, vit. C, vit. E, calcium, iron, magnesium, potassium
j (disqualifying nutrients): saturated fat, sodium, added sugar
RDV: recommended daily value
MRV: maximum recommended daily value

Although using the same qualifying and disqualifying nutrients as the NRF9.3, the NQI developed by Sonesson et al considers the total consumption of nutrients in a diet in relation to their dietary needs (U. Sonesson et al., 2019).

$$\text{NQI} = \sum_{i=1}^{i=9}\left(\text{NQI}_{qual_i}\right) - \sum_{j=1}^{j=3}\left(\text{NQI}_{disqual_j}\right) \qquad (2a)$$

$$\text{NQI}_{qual_i} = \frac{\text{ratio in product}}{\text{ratio in diet}} \div \text{consumption ratio} \qquad (2b)$$

$$\text{NQI}_{disqual_j} = \frac{\text{ratio in product}}{\text{ratio in diet}} \times \text{consumption ratio} \qquad (2c)$$

$$\text{consumption ratio} = \frac{\text{dietary intake}}{\text{dietary need}} \qquad (2d)$$

To incorporate the satiety context into food LCA, a new FU based on FullnessFactor™ (FF), a simple objective mean to quantify the satiety response of food developed by NutritionData (NutritionData, 2018b). The FF is calculated as:

$$\text{FF}_{original} = \frac{41.7}{a^{0.7}} + 0.05b + 6.17 \times 10^{-4}c^3 - 7.25 \times 10^{-6}d^3 + 0.617 \qquad (3a)$$

where $0.5 \leq \text{FF}_{original} \leq 5.0$
a: kcal per 100 g of food
b: grams of protein per 100 g of food
c: grams of dietary fiber per 100 g of food
d: grams of total fat per 100 g of food

$$FF = \text{FF}_{original} \times \text{g of food item consumed per 2000 kcal diet} \qquad (3b)$$

As shown in Eq. 3a, the $\text{FF}_{original}$ of a food is proportional to its protein and dietary fiber contents and is inversely proportional to its energy and total fat contents. A scaled $\text{FF}_{original}$ was found to correlate well with the experiments conducted by Holt et al that recorded the satiety responses of human subjects to thirty-six foods (Holt, Miller, Petocz, & Farmakalidis, 1995; NutritionData, 2018a). To compare all the dietary patterns on an isocaloric basis of 2000 kcal, FF used as a FU was defined by multiplying $\text{FF}_{original}$ by the total weight of food consumed in a 2000 kcal diet, as shown in Eq. 3b.

Higher values of NRF9.3 and FF indicate improved nutrition and satiety, respectively. However, the optimal NQI is 1, indicating intakes of qualifying nutrients that match their dietary need. Higher values of NQI indicate a dietary inadequacy such as a short fall in one or more of the qualifying nutrients; whereas negative values of NQI indicate that the qualifying nutrients in the food are outweighed by the disqualifying nutrients in a particular dietary context.

The NRF9.3, NQI, and FF of individual foods and diets can be calculated based on mass, energy, amount of daily portion, or other specific references Since the objective of this study was to compare different daily dietary patterns, the daily portion basis was used.

2.2 Food database

The eating patterns studied here were constructed from a variety of foods within each of fourteen categories/subcategories specified in the Dietary Guidelines for Americans, as shown in Table 2.1. This list of foods in Table 2.1 was derived from the food availability and consumption statistics provided by the U.S. Department of Agriculture's Economic Research Service (USDA ERS), specifically the loss adjusted food availability databases (ERS, 2016). Data from the most recently updated year of 2016 or the closest year (when the 2016 data was not available) was utilized. A sufficient variety of foods in each category were selected to account for greater than 90% of annual consumption in the U.S. The nutrient composition of each food listed in Table 2.1 was obtained from the USDA National Nutrient Database and used to calculate the nutrient index scores (i.e., NRF9.3 and NQI) of the recommended daily portion of each food category in different dietary patterns studied on an isocaloric basis of 2000 kcal.

Table 2.1. Categories and selected component foods

Category	**Food items**	**Source of LCA Data**
Dark green vegetables (DGV)	asparagus, broccoli, celery, head lettuce, kale, leaf lettuce, spinach	Ecoinvent 3.4
Red & orange vegetables (ROV)	beets, carrots, red bell pepper, tomato	Ecoinvent 3.4
Legumes (LEG)	black beans, chick peas, fava beans, lentils, navy beans, pinto beans	Ecoinvent 3.4
Starchy vegetables (STV)	corn, peas, potato	Ecoinvent 3.4

Table 2.1 continued

Other vegetables (OTV)	cabbage, cucumber, eggplant, green bell pepper, mushrooms*, onion, zucchini	Ecoinvent 3.4, *(Robinson, Winans, Kendall, Dlott, & Dlott, 2019)
Fruit (FRT)	apple, apricot, avocado, banana, blueberry*, cantaloupe, grapes, kiwi, lemon, orange, pear, strawberry, watermelon	Ecoinvent 3.4, *(Chapa, Salazar, Kipp, Cai, & Huang, 2019)
Whole grains (WGN)	barley, brown rice, oats, whole wheat bread*’	Ecoinvent 3.4, *(Espinoza-Orias, Stichnothe, & Azapagic, 2011)
Refined grains (RGN)	pasta*’,white bread†’, white rice	Ecoinvent 3.4, *(Ruini, Ferrari, Meriggi, Marino, & Sessa, 2013), †(Espinoza-Orias et al., 2011)
Dairy (DRY)	skim milk, 1% milk, 2% milk, whole milk, whole-milk cheddar cheese, whole-milk mozzarella cheese, non-fat dry milk, soymilk, plain yogurt, strawberry yogurt	Ecoinvent 3.4
Seafood (SEA)	salmon, sardines*, tilapia†	Ecoinvent 3.4, *(Almeida, Vaz, & Ziegler, 2015), †(Yacout, Soliman, & Yacout, 2016)
Meat, poultry & eggs (MPE)	lean beef (90/10)*, fatty beef (75/25)*, chicken†, eggs[1], pork[2]	*(Asem-Hiablie, Battagliese, Stackhouse-Lawson, & Alan Rotz, 2019), †(Pelletier, 2008), [1](Quantis, 2014), [2](Putnam, 2018)
Soy, nuts & seeds (SNS)	almonds, peanuts, soy veggie burger patty*’, sunflower seeds	Ecoinvent 3.4, *(Quantis, 2016)
Oil (OIL)	canola oil, olive oil, palm oil, peanut oil, soybean oil, sunflower oil	Ecoinvent 3.4
Discretionary (DIS)	butter, carbonated cola soft-drink*’, cheeseburger, pepperoni pizza†’	Ecoinvent 3.4, *(Amienyo, Gujba, Stichnothe, & Azapagic, 2013), † (Stylianou, Nguyen, Fulgoni, & Jolliet, 2017)

*, †, [1], or [2] indicates data source if other than Ecoinvent 3.4; ' indicates GWP impact data only

2.3 Dietary Patterns

The FUs were applied and evaluated using four American dietary contexts including the foods shown in Table 2.1. These diets were: (i) recommended healthy U.S., (ii) recommended Mediterranean, (iii) recommended vegetarian, and (iv) "typical" U.S. The first three diets were formatted for one-day food intake by adapting the daily recommendations for each category/subcategory given in the Dietary Guidelines for Americans. The reference intakes were converted from cup- or ounce-equivalent units to standardized grams using the conversion factor for each food in the loss adjusted food availability databases (ERS, 2016). The "typical" U.S. dietary pattern was constructed using the information from the Dietary Guidelines for Americans and from the USDA ERS, which assesses the conformity of the eating habits of American population to the dietary recommendations. An additional dietary pattern, unhealthy U.S., was constructed from popular and commonplace foods and developed to represent a scenario that is nutritionally worse than the recommended and "typical" diets. All dietary patterns were compared on an isocaloric basis of 2000 kcal, which is used as the basis for nutritional labeling and representative for the majority of the country's adult population. Therefore, the recommended intake of every selected food item in the healthy U.S., Mediterranean, and vegetarian diets was scaled proportionally to make the total calories of each diet 2000 kcal. A sensitivity analysis was performed to assess the effects of increasing daily caloric consumption.

An example day of eating including three meals and snacks according to each dietary pattern was constructed to better demonstrate a concrete picture of the diets that can be adopted by consumers. The examples, as shown in Table 2.2, were populated with foods shown in Table 2.1 and based on the following sources. The example healthy U.S. and Mediterranean meals were based on the sample 2-week menu provided by the USDA ChooseMyPlate guide and the work of Migala (Migala, 2019). The example vegetarian meals were extracted from an example

7-day vegetarian meal plan (Seaver, 2018). The "typical" U.S. example meals consisted of the same food items as the healthy U.S. example, but with adjusted proportions of food items from each category as discussed in the methodologies section. The unhealthy U.S. example was composed of food items with poor nutrient quality, in terms of low qualifying and high disqualifying nutrients, that are popularly consumed by Americans for meals and snacks.

Table 2.2. Example meals for each dietary pattern

	Healthy U.S.	**Mediterranean**	**Vegetarian**	**"Typical" U.S.**	**"Unhealthy" U.S.**
Meal 1	banana, 1% milk, oatmeal	almonds, orange, strawberries, yogurt	almonds, eggs, oats, strawberry, yogurt	banana, 1% milk, oatmeal	butter, cheddar cheese, eggs, white bread
Meal 2	white bread, butter, sardines, chickpeas, cucumber, broccoli	salmon, broccoli, lentils, brown rice, potato, butter	lettuce, tomato, cucumber, olive oil, white bread, mozzarella cheese	white bread, butter, sardines, chickpeas, cucumber, broccoli	cheeseburger, potato, tomato
Meal 3	split peas, corn, canola oil, chicken, brown rice	chicken, mozzarella cheese, tomato, eggplant, mushrooms, pasta, olive oil	broccoli, onion, zucchini, brown rice, butter	split peas, corn, canola oil, chicken, brown rice	pepperoni pizza, cola
Snacks	carrots, peanuts	grapes, sardines	apple, cheddar cheese, peanuts	carrots, peanuts	ice cream

2.4 Life cycle inventory and impact assessment

As shown in Table 2.1, the LCA data on the food items was primarily collected from the Ecoinvent v3.4 database (Wernet et al., 2016). Data unavailable in the database was supplemented by published LCA literature as indicated in Table 2.1. The midpoint environmental impacts associated with dietary choices were assessed by SimaPro v8.5.2 using

ReCiPe Midpoint Egalitarian v1.02 methodology (PRé Consultants, Netherlands). Here we selectively presented the results of global warming potential (GWP), terrestrial acidification (AP) and freshwater eutrophication (EP) only because they have been proven the most important environmental impacts associated with agricultural production (Rice & Herman, 2012; Wagner & Lewandowski, 2017).

3. Results

3.1 Environmental performance of dietary patterns

3.1.1 Nutrient and satiety indices of food categories

Table 2.3 shows the portion-scaled values of three nutrient and satiety indices (i.e. NRF9.3, NQI, and FF) of fourteen food categories, which highly depended on the dietary patterns. The highest mean and high values of NRF9.3 were obtained by dairy in the healthy U.S. and vegetarian diets, which can be attributed to the higher consumption of dairy in these diets and the significant contributions to the qualifying nutrients, especially protein, calcium, and potassium, made by low-fat dairy products. The lowest value mean and low values of NRF9.3 were obtained by the discretionary category in the vegetarian diet, which occurred because these foods contain larger amounts of disqualifying than qualifying nutrients, making their scores negative. Meat containing cheeseburger and pepperoni pizza were excluded from the discretionary category in the vegetarian diet such that this category comprised only soda and butter, resulting in slightly lower mean and low values than in the other dietary patterns. The highest mean value of NQI was obtained by dark green vegetables in the "typical" U.S. diet due to significant contributions to micronutrients such as vitamin A, vitamin C, magnesium, and potassium and absence of disqualifying nutrients. However, the highest high value of NQI was obtained by seafood in the “typical” U.S. diet. The lowest mean and low values of NQI were obtained by discretionary foods in the Mediterranean diet. The highest mean and high FF were obtained by dairy in the healthy U.S. and vegetarian diets. The lowest mean and low FF were obtained by oil in the healthy U.S., Mediterranean, and “typical” U.S. diets.

In many cases the portion-scaled values of NRF9.3 and FF were equal across dietary patterns (except for the “typical” U.S. diet) because their amounts in those diets were equal. In contrast, the NQI value of every single food category changed across dietary patterns, because it is calculated based on the total dietary context (Eq. 2), and can thus be affected by any changes in the amount of other food categories. For instance, the NQI of the category of meat, poultry, and eggs in the vegetarian diet (509.54) was different from those in other diets not only because it was calculated based on eggs only, but also because the proportions of foods in the other categories, such as whole grains and nuts, seeds, and soy products, were different. These differences in turn affected the consumption ratio of each of the qualifying and disqualifying nutrients, resulting in different NQI depending on dietary patterns. Similar to the high NQI of eggs in the vegetarian food pattern, a high NQI, of 516.74, can be obtained by the seafood category in the “typical” U.S. diet because the rest of the diet components are extremely poor, in terms of the ratio of qualifying and disqualifying nutrients. Caution must be taken when attempting to compare environmental impacts on an NQI basis in the same way as on a mass, NRF9.3, or FF basis because a higher NQI depends strongly on the consumption ratio and is indicative of a diet with lower nutritional quality than recommended in terms of the qualifying and disqualifying nutrients; the total NQI is high because some of the foods supply short fall nutrients.

Table 2.3 Nutrition and satiety indices of different food categories in the healthy U.S. diet (HUS), Mediterranean diet (MED), vegetarian diet (VEG), and "typical" diet (TYP) for a 2000 kcal day

		NRF9.3			**NQI**			**FF**		
		Low	**Mean**	**High**	**Low**	**Mean**	**High**	**Low**	**Mean**	**High**
DGV	HUS	0.07	0.46	1.28	0.50	10.56	151.85	0.32	0.91	1.93
	MED	0.07	0.46	1.28	0.39	9.01	138.45	0.32	0.91	1.93
	VEG	0.07	0.46	1.28	0.35	8.32	109.51	0.32	0.91	1.93
	TYP	0.03	0.22	0.60	0.60	17.43	345.64	0.15	0.43	0.90
ROV	HUS	0.46	3.75	9.49	0.71	9.27	39.26	3.96	5.02	5.86
	MED	0.46	3.75	9.49	0.56	7.68	39.25	3.96	5.02	5.86
	VEG	0.46	3.75	9.49	0.52	7.05	27.74	3.96	5.02	5.86
	TYP	0.21	1.72	4.35	0.74	16.23	74.07	1.82	2.30	2.68
LEG	HUS	0.26	0.38	0.44	3.05	14.83	148.74	2.51	2.79	3.05
	MED	0.26	0.38	0.44	2.44	12.90	144.21	2.51	2.79	3.05
	VEG	0.26	0.38	0.44	2.27	10.92	88.17	2.51	2.79	3.05
	TYP	0.12	0.18	0.20	2.84	15.28	381.33	0.41	0.49	0.57
STV	HUS	0.63	1.03	1.37	1.70	5.15	54.09	2.77	4.04	5.33
	MED	0.63	1.03	1.37	1.43	4.11	52.31	2.77	4.04	5.33
	VEG	0.63	1.03	1.37	1.27	3.63	42.23	2.77	4.04	5.33
	TYP	0.55	0.90	1.19	1.78	5.59	82.40	2.41	3.50	4.63
OTV	HUS	0.11	0.44	1.26	-0.18	4.50	152.49	2.42	3.43	4.28
	MED	0.11	0.44	1.26	-0.28	3.76	150.25	2.42	3.43	4.28
	VEG	0.11	0.44	1.26	-0.27	3.49	103.65	2.42	3.43	4.28
	TYP	0.12	0.48	1.37	-0.12	6.78	205.39	2.62	3.73	4.65
FRT	HUS	0.66	2.98	7.58	-0.04	6.47	22.41	6.22	10.67	14.83
	MED	0.82	3.73	9.48	-0.18	5.30	18.80	7.78	13.33	18.54
	VEG	0.66	2.98	7.58	-0.21	4.69	18.70	6.22	10.67	14.83
	TYP	0.30	1.34	3.41	0.01	9.54	43.85	2.80	4.80	6.67

Table 2.3 continued

WGN	HUS	0.26	0.74	1.58	-0.28	12.73	92.67	1.87	2.06	2.41
	MED	0.26	0.74	1.58	-0.56	11.29	92.24	1.87	2.06	2.41
	VEG	0.30	0.86	1.85	-0.64	9.47	61.04	2.18	2.40	2.81
	TYP	0.26	0.74	1.58	-0.18	12.89	151.79	1.87	2.06	2.41
RGN	HUS	0.20	0.32	0.44	-0.70	5.10	50.59	1.57	1.73	1.81
	MED	0.20	0.32	0.44	-1.09	4.43	51.04	1.57	1.73	1.81
	VEG	0.20	0.32	0.44	-0.93	4.12	37.13	1.57	1.73	1.81
	TYP	0.24	0.38	0.53	-0.79	5.08	53.22	1.88	2.07	2.18
SEA	HUS	0.22	0.30	0.45	0.32	8.56	246.81	0.92	0.99	1.08
	MED	0.41	0.56	0.84	0.48	8.46	167.59	2.83	3.04	3.32
	VEG	-	-	-	-	-	-	-	-	-
	TYP	0.22	0.30	0.45	0.66	9.51	516.74	0.92	0.99	1.08
SNS	HUS	0.18	0.70	1.15	1.76	35.01	220.33	0.35	0.44	0.52
	MED	0.18	0.70	1.15	0.89	30.23	192.07	1.71	2.18	2.59
	VEG	0.89	3.46	5.71	14.58	20.52	22.68	1.45	1.85	2.20
	TYP	0.47	1.82	3.00	1.70	25.88	101.80	0.47	1.82	3.00
OIL	HUS	0.04	0.57	1.29	-6.11	12.40	95.92	0.14	0.14	0.14
	MED	0.04	0.57	1.29	-9.57	8.01	74.59	0.14	0.14	0.14
	VEG	0.04	0.57	1.29	-10.82	-1.77	46.79	0.14	0.14	0.14
	TYP	0.10	1.35	3.05	-9.38	-1.97	12.21	0.32	0.32	0.32
DRY	HUS	-0.43	2.58	10.25	-10.81	2.57	29.43	7.05	18.82	31.23
	MED	-0.06	0.56	2.85	-10.22	3.06	33.23	4.70	12.55	20.82
	VEG	-0.43	2.58	10.25	-9.32	3.51	28.49	7.05	18.82	31.23
	TYP	-0.22	1.29	5.12	-7.61	5.21	40.32	3.52	9.41	15.61
MPE	HUS	0.17	0.41	0.71	-1.54	3.76	121.20	2.19	2.95	3.40
	MED	0.17	0.41	0.71	-2.28	3.43	108.53	2.19	2.95	3.40
	VEG	0.07	0.07	0.07	0.32	2.24	509.54	0.28	0.28	0.28
	TYP	0.18	0.45	0.76	-1.88	4.73	140.20	2.35	3.18	3.66

Table 2.3 continued

DIS	HUS	-1.01	-0.14	0.43	-21.57	-3.70	41.87	0.19	8.29	28.84
	MED	-1.01	-0.14	0.43	-24.24	-4.40	39.78	0.19	8.29	28.84
	VEG	-1.01	-0.64	-0.27	-22.35	-3.83	30.66	0.19	14.51	28.84
	TYP	-1.01	-0.14	0.43	-22.67	-1.40	24.77	0.19	8.29	28.84

DGV = dark green vegetables, ROV = Red and orange vegetables, LEG = legumes, STV = starchy vegetables, OTV = other vegetables, FRT = fruit, WGN = whole grain, RGN = refined grain, DRY = dairy, SEA = seafood, MPE = meat, poultry, and eggs, SNS = soy, nuts, and seeds, OIL = oil, DIS = discretionary

The foods selected within each category vary in terms of physical properties, water content, energy density, and nutrient composition, which results in a large variation in their amounts (masses) that provide 2000 kcal while meeting the daily intakes recommended by the Dietary Guidelines for Americans, as shown in Table 2.4. For example, the typical U.S. diet had the lowest total food mass for 2000 kcal due to the lower consumption of low energy density vegetables, and higher consumption of high energy density oil. Conversely, higher total food masses required by the Mediterranean diet were associated with higher consumption of any beverages as well as fruits and vegetables, which have high water and dietary fiber contents and low energy density.

3.1.2 GWP of dietary patterns

Table 2.4 also shows the GWP of the four dietary patterns calculated using different FU. It is apparent that the vegetarian diet had the lowest mean GWP on a mass basis. Although the typical U.S. diet had the second lowest mean GWP on a mass basis, due to its lower nutritional quality in comparison with the three recommended food patterns, it produced the highest mean GWP based on NRF9.3. On the FF basis, the vegetarian diet showed the lowest mean GWP, which can be attributed to higher consumption of soy, nuts, and seeds, which can induce higher satiety when compared to the other dietary patterns, and the absence of meat products, which result in higher GWP.

Table 2.4. Mean values of total mass and total GWP of four dietary patterns calculated scaled by different FU on a 2000 kcal basis

Dietary pattern	**Total food mass (g)**	**Total GWP-mass in diet (kg CO_2 eq.)**	**Total GWP-NRF9.3 (kg CO_2 eq./NRF9.3)**	**Total mean GWP-NQI (kg CO_2 eq./NQI)**	**Total GWP-FF (kg CO_2 eq./ FF)**
HUS	1685 ± 672	6.71	0.462	0.053	0.108
MED	1836 ± 626	6.26	0.385	0.058	0.100
VEG	1682 ± 612	3.88	0.239	0.054	0.058
TYP	1379 ± 519	6.10	0.555	0.047	0.141

Figure 2.1 shows the mass-based GWP profiles of the food categories included in different dietary patterns. The mean GWP showed differences between vegetarian and the other two recommended food patterns in the categories of soy, nuts, and seeds and discretionary. The vegetarian diet has a higher impact in soy, nuts, and seeds due to increased consumption, but a higher impact in discretionary due to consideration of only soda and butter within the discretionary category since meat containing cheeseburger and pepperoni pizza were eliminated in this case. Dairy, discretionary, meat, poultry, and eggs categories revealed the highest GWP based on the mass consumed across the dietary patterns. The high recommended consumption of dairy could make the healthy U.S. and vegetarian food patterns less environmentally sustainable than the Mediterranean and "typical" U.S. diets, unless lower carbon footprint dairy options are chosen. Table 2.5 shows the GWP of one kilogram of selected foods within the categories of dairy, meat, poultry, eggs, and discretionary. Because dairy, meat, poultry, and eggs are commonly eaten to satisfy these functions, Table 2.5 also shows the GWP based on energy and protein content per kg of food. Among the dairy foods, cheeses generated higher GWP than ice

cream, yogurt, milk, and soymilk (included in the dairy category in accordance with the Dietary Guidelines for Americans). This is because of the additional processing steps required for converting milk to cheese and the resulting cheese yield (approximately 10,000 liters of milk for 1 ton of cheese), which will be discussed further in the next section. Furthermore, in the category of meat, poultry, and eggs, beef had the highest GWP, which agreed with many previous LCA studies (Asem-Hiablie et al., 2019; de Vries & de Boer, 2010; Heller & Keoleian, 2015; Ulf Sonesson, Davis, Flysjö, Gustavsson, & Witthöft, 2017), and eggs are the most sustainable option. As to the discretionary category, after soda, pizza had the lowest GWP due to the significant contribution of wheat grain to its total mass. Similarly, cheese burger also had lower GWP than beef in the same mass because it comprises beef, cheese, and wheat-based buns.

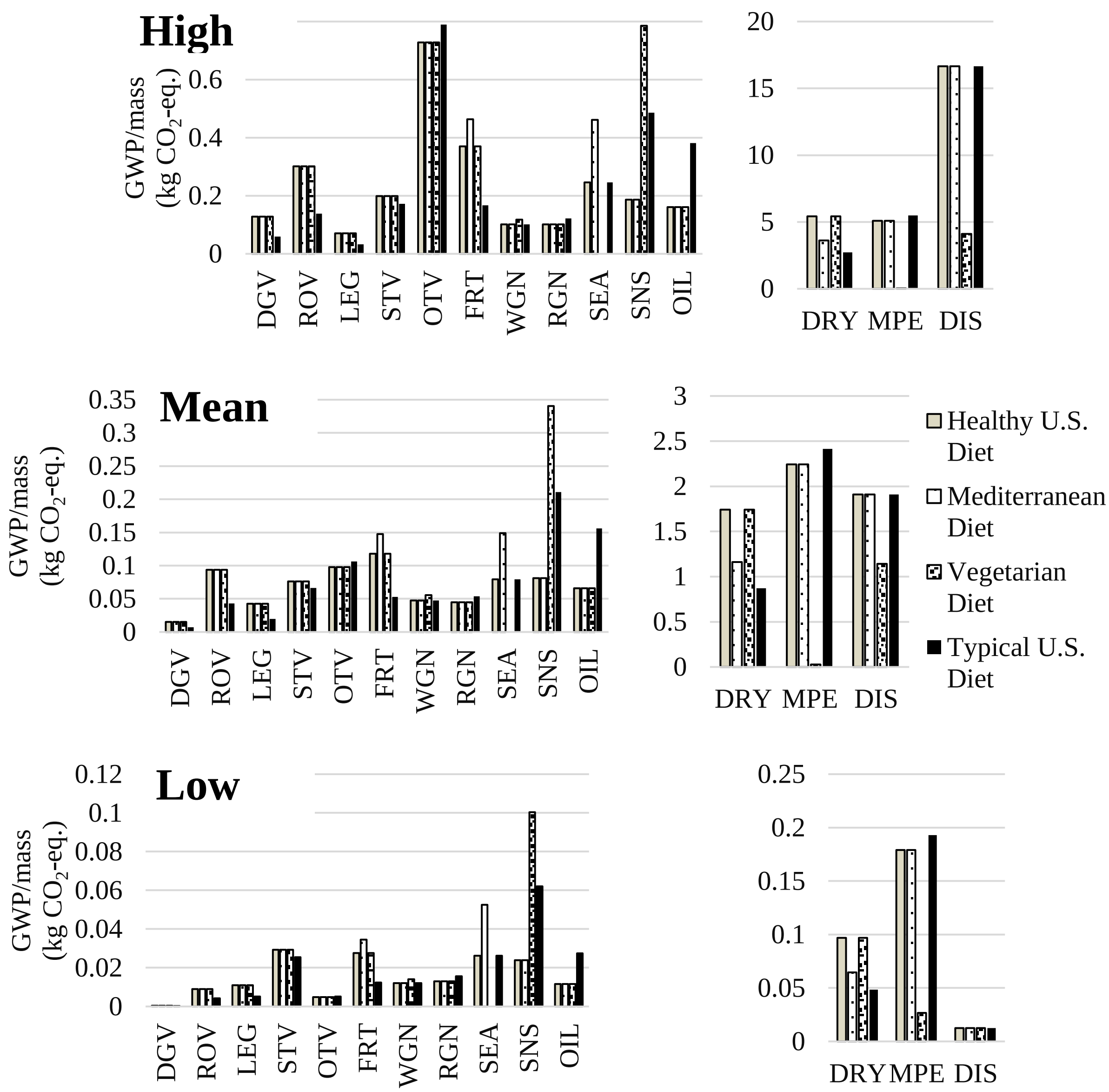


Figure 2.1. Mass-based GWP profiles of food categories in different dietary patterns within 2000 kcal daily consumption. High and low values demonstrate the range that can be obtained by selection of foods within each category.

Table 2.5. GWP of selected foods in dairy, meat, poultry, eggs, and discretionary categories

Dairy	**GWP/mass** (kg CO_2 eq./kg of food)	**GWP/energy** (kg CO_2 eq./kcal per kg)	**GWP/protein** (kg CO_2 eq./g of protein per kg)
whole milk cheddar cheese	7.39	0.0018	0.0297
whole milk mozzarella cheese	6.35	0.0021	0.0286
non-fat dry milk	6.07	0.0017	0.0168
ice cream	3.57	0.0017	0.1019
strawberry yogurt	3.51	0.0034	0.0925
plain yogurt	1.26	0.0021	0.0360
skim milk	1.12	0.0032	0.0330
whole milk	0.91	0.0015	0.0284
2% milk	0.85	0.0017	0.0258
1% milk	0.81	0.0019	0.0238
soymilk	0.29	0.0005	0.0087
Meat, Poultry, & Eggs			
lean beef (90/10)	48.40	0.0226	0.1820
chicken (boneless-skinless breast)	1.70	0.0015	0.0079
pork (top loin)	5.90	0.0035	0.0203
eggs	2.19	0.0013	0.0197
Discretionary			
butter	5.62	0.0008	0.6244
soda	0.33	0.0009	0.3320
cheese burger	22.80	0.0087	0.1754
pepperoni pizza	2.80	0.0010	0.0233

Figure 2.2 demonstrates the NRF9.3-based GWP profiles of the food categories included in different dietary patterns. The mean GWP showed differences between other vegetables and the

dark green, red, and orange vegetable categories, due to the comparatively lower average qualifying nutrient content of the other vegetables. Whole grain outperformed refined grain and starchy vegetables, exhibiting lower GWP based on NRF9.3. The vegetarian food pattern was noticeably distinct from the other three patterns due to no seafood consumption, and only eggs consumption in the meat, poultry, and eggs category. Since the discretionary category exhibited a negative mean NRF9.3 for all four dietary patterns, its NRF9.3-based GWP was infinitely high in principle, suggesting the environmental performance of these diets can be improved by switching discretionary foods to other categories. Moreover, although similar to mass-based GWP profile (Figure 2.1) that the meat, poultry eggs and dairy categories were the other two major contributors to the GWP, meat, poultry eggs had a higher mean value than dairy, except for the Mediterranean diet.

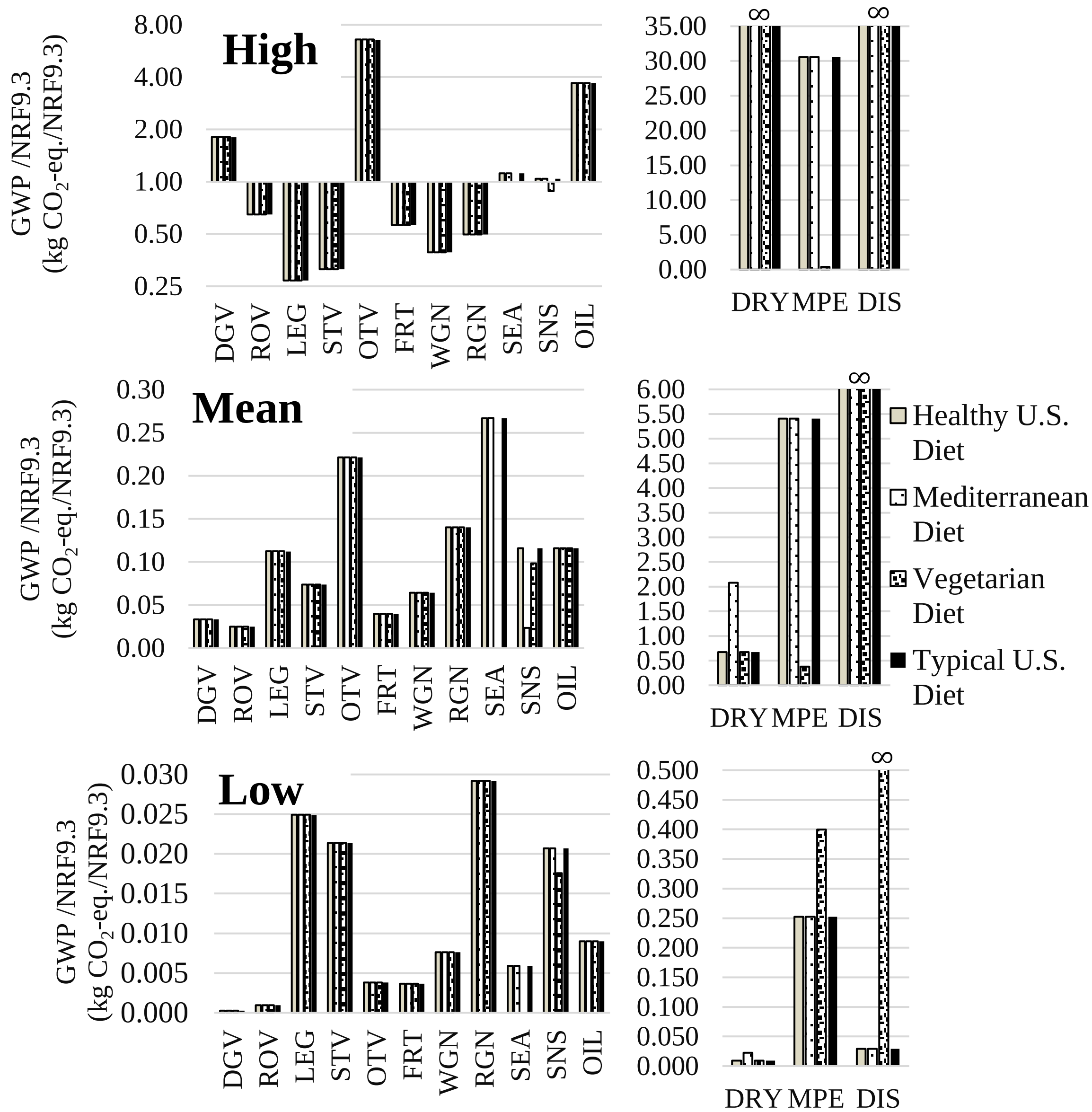


Figure 2.2. NRF9.3-based GWP profiles of food categories in different dietary patterns within 2000 kcal daily consumption. High and low values demonstrate the ranges that can be obtained by selection of foods within each category.

Figure 2.3 presents the NQI-based GWP profiles of the food categories included in different dietary patterns. The mean GWP showed that all types of vegetables, as well as grains, seafood, soy, nuts and seeds, can be considered more sustainable than meat, poultry, eggs, dairy, and the low nutrient quality foods selected in the discretionary category. The potential infinity of GWP (represented by the high bars) shown in several categories indicated that all the four diets could theoretically be unsustainable because these categories included some foods with negative NQI values (Table 2.3), which need to be removed from the diets in order to improve their environmental performance (Sonesson et al., 2019). In contrast, dark green vegetables, red and orange vegetables, starchy vegetables, and legumes, as well as seafood, soy nuts and seeds exhibited lower GWP ranges than the other categories, suggesting that their consumption following the proportions recommended by the Dietary Guidelines for Americans was more sustainable on the NQI basis. However, the high and low bars of each category show the extreme cases which occur only when all the other foods selected in the diet have the maximum or minimum qualifying and disqualifying nutrients.

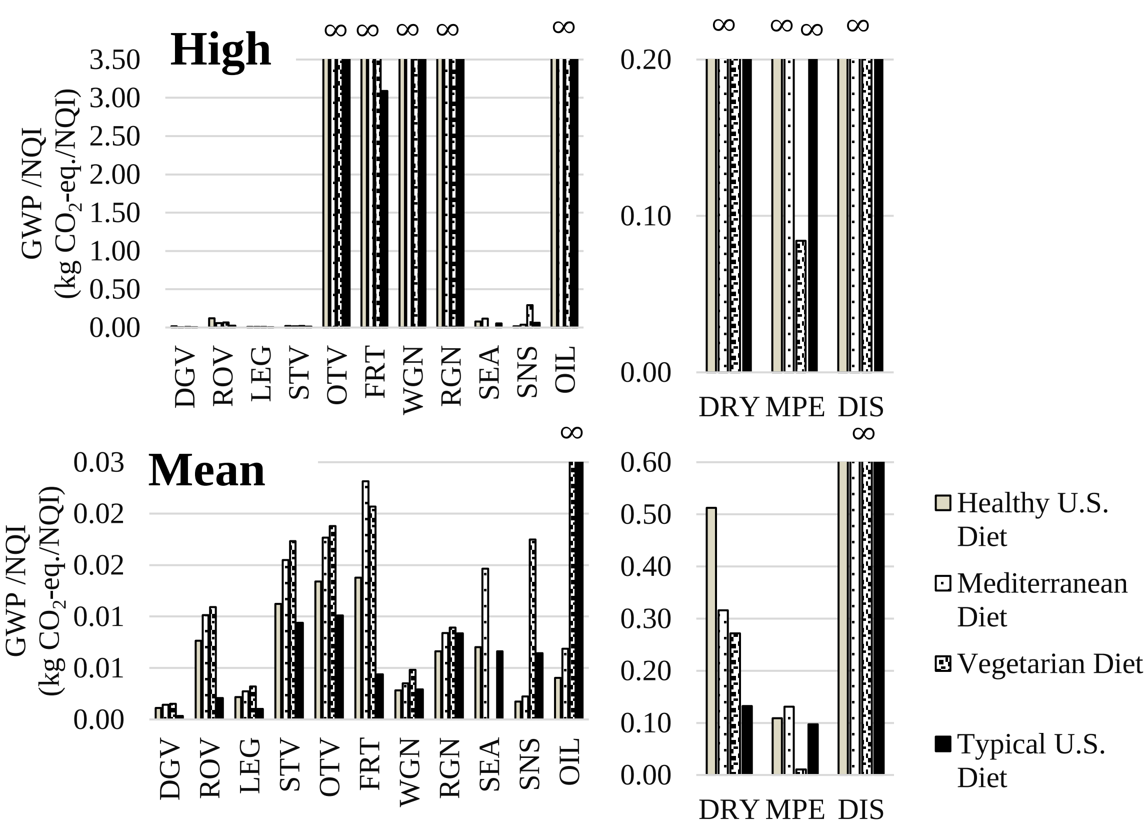


Figure 2.3. NQI-based GWP profiles of food categories in different dietary patterns within 2000 kcal daily consumption. High and low values demonstrate the ranges that can be obtained by selection of foods within each category.

Figure 2.3. continued

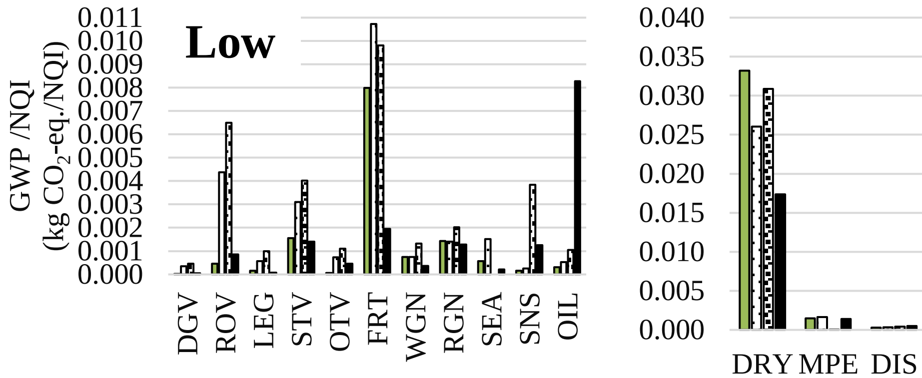


Figure 2.4 shows the FF-based GWP profiles of the food categories included in different dietary patterns. The results indicated that vegetables, fruits, and grains were the most sustainable due to their high satiety values (Table 2.3), and high energy density foods like butter within the discretionary category and oil appeared the least environment-friendly.

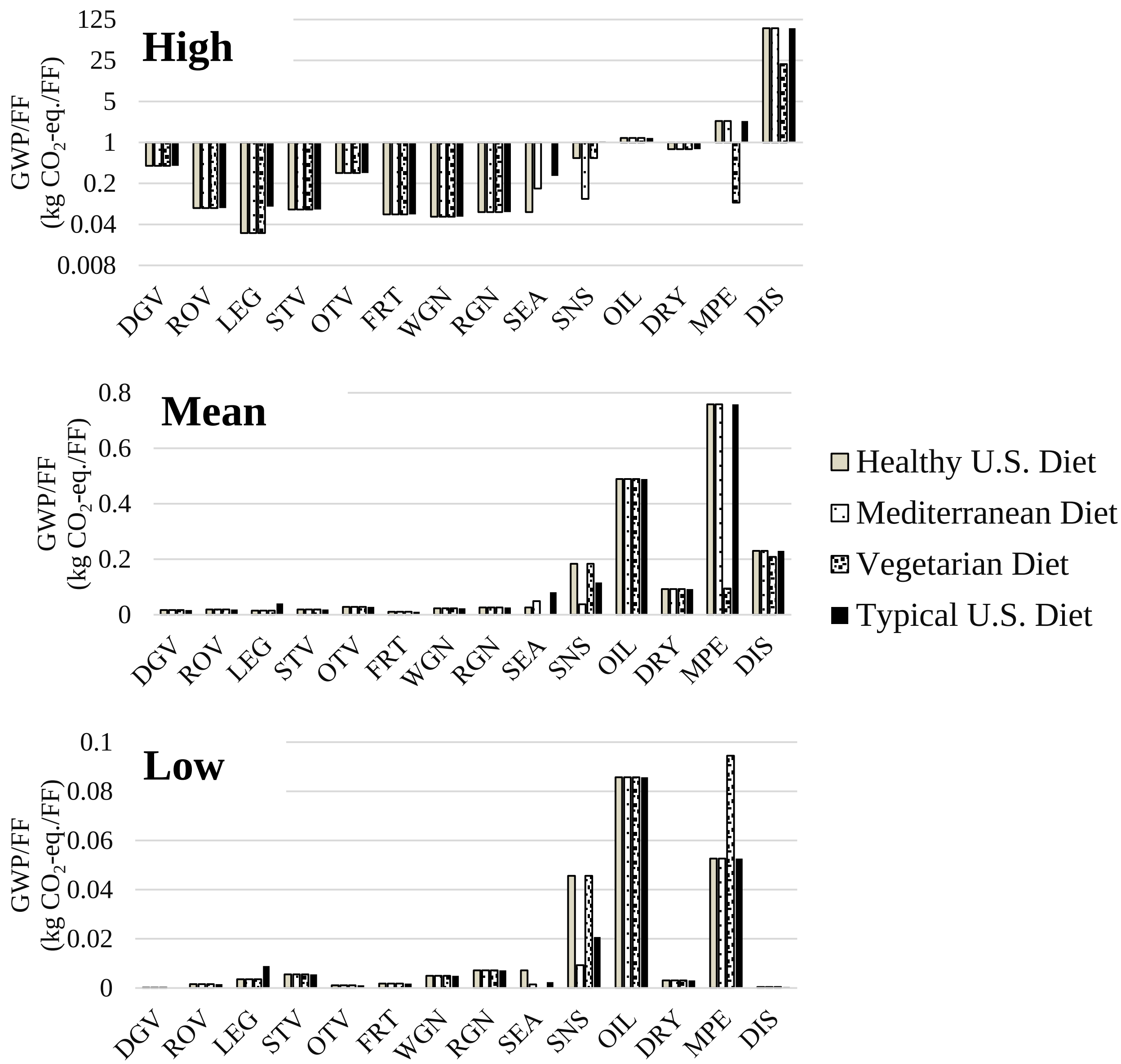


Figure 2.4. FF-based GWP profiles of food categories in different dietary patterns within 2000 kcal daily consumption. High and low values demonstrate the ranges that can be obtained by selection of foods within each category.

Figure 2.5 compares the total GWP of four dietary patterns calculated using different FU. Overall, the mean values of all the diets were fairly similar regardless of the FU, although the nominal mean GWP of the "typical" U.S. diet based on NRF9.3 and FF was more than double the vegetarian diet largely due to lower consumption of all vegetables and the higher GWP associated with meat and poultry consumption. In the meantime, the large ranges of the obtained

GWP in all the cases indicated that any dietary pattern could be more sustainable than the others if it is constructed in a way that the lowest GWP foods in each category are selected to meet energy and nutritional needs.

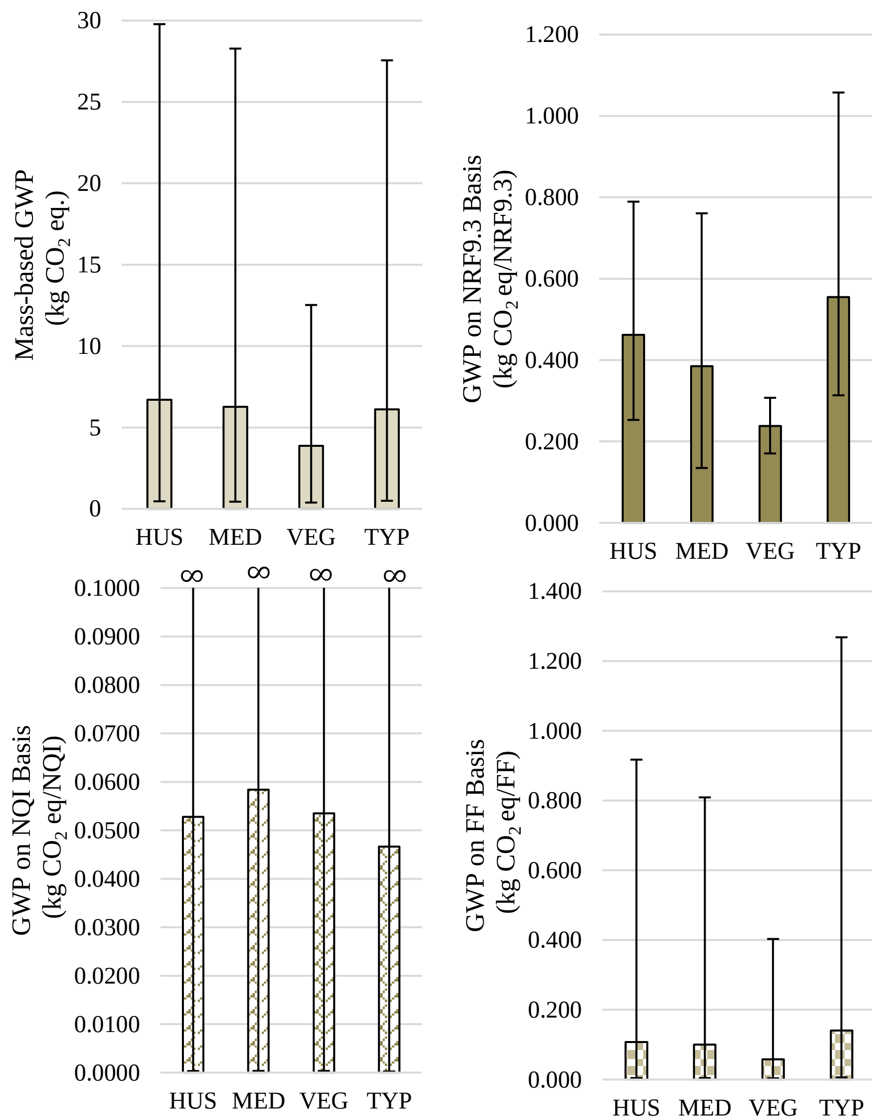


Figure 2.5. Total GWP of four dietary patterns (per 2000 kcal diet) based on different FU. Error bars refer to range of the values.

3.1.3. AP and EP of dietary patterns

Table 2.6 presents the mass-based AP and EP associated with different food categories. It is apparent that meat, poultry and eggs, discretionary, dairy, and refined grains were the main contributors to AP. The main contributors to EP were refined grains, meat poultry and eggs, seafood, and dairy.

Table 2.6. Mass-based acidification and eutrophication potentials of different food categories

	EP (kg P-eq.)/kg			**AP (kg SO_2-eq.)/kg**		
	Low	Mean	High	Low	Mean	High
DGV	3.37×10^{-6}	2.84×10^{-4}	1.27×10^{-3}	-1.12×10^{-3}	4.14×10^{-3}	1.54×10^{-2}
ROV	2.97×10^{-5}	3.11×10^{-4}	9.79×10^{-4}	5.84×10^{-4}	4.28×10^{-3}	1.08×10^{-2}
LEG	8.44×10^{-5}	2.43×10^{-4}	3.03×10^{-4}	2.21×10^{-3}	7.05×10^{-3}	1.15×10^{-2}
STV	7.12×10^{-5}	1.72×10^{-4}	2.44×10^{-4}	4.79×10^{-3}	5.03×10^{-3}	5.35×10^{-3}
OTV	2.97×10^{-5}	4.06×10^{-4}	2.38×10^{-4}	2.89×10^{-4}	6.43×10^{-3}	1.97×10^{-2}
FRT	6.70×10^{-5}	1.57×10^{-4}	3.20×10^{-4}	7.63×10^{-4}	2.77×10^{-3}	7.54×10^{-3}
WGN	1.92×10^{-4}	4.74×10^{-4}	9.83×10^{-4}	4.90×10^{-3}	1.50×10^{-2}	2.09×10^{-2}
RGN	2.48×10^{-4}	6.49×10^{-2}	1.30×10^{-1}	1.91×10^{-2}	1.91×10^{-2}	1.91×10^{-2}
DRY	7.70×10^{-5}	2.43×10^{-3}	6.60×10^{-3}	1.44×10^{-3}	6.31×10^{-2}	1.80×10^{-1}
SEA	8.18×10^{-6}	7.07×10^{-3}	1.10×10^{-2}	6.66×10^{-4}	1.86×10^{-2}	3.80×10^{-2}
MPE	4.14×10^{-4}	8.39×10^{-3}	2.00×10^{-2}	1.93×10^{-2}	3.18×10^{-1}	7.26×10^{-1}
SNS	3.89×10^{-4}	7.34×10^{-4}	8.09×10^{-4}	5.01×10^{-3}	1.42×10^{-2}	2.61×10^{-2}
OIL	2.06×10^{-4}	5.19×10^{-4}	8.09×10^{-4}	6.84×10^{-3}	1.80×10^{-2}	3.13×10^{-2}
DIS	1.32×10^{-3}	1.44×10^{-3}	1.57×10^{-3}	4.30×10^{-2}	1.99×10^{-1}	3.56×10^{-1}

Figure 2.6 shows the AP profiles of the four dietary patterns calculated using different FU. Based on the proportions of the food categories consumed in the typical U.S. diet, dairy had the highest mass-based AP, followed by meat, poultry and eggs, except for the vegetarian diet, in which the absence of beef, poultry and pork consumption accounted for its lower mass-based AP (Figure 2.6a). Refined grains also produced a significant amount of mass-based AP, primarily

due to the impacts of white rice, which could be reduced by shifting to higher whole grain consumption.

In Figure 2.6b, the discretionary foods showed the highest NRF9.3-based AP because of their negative NRF9.3 score, indicating that the NRF9.3 score of a diet would be improved by removing these foods. Dairy exhibited a higher NRF9.3-based AP in the Mediterranean diet due to its lower proportion in this food pattern, resulting in lower contribution to the daily requirements of qualifying nutrients. Refined grains were also a significant contributor to the NRF9.3-based AP.

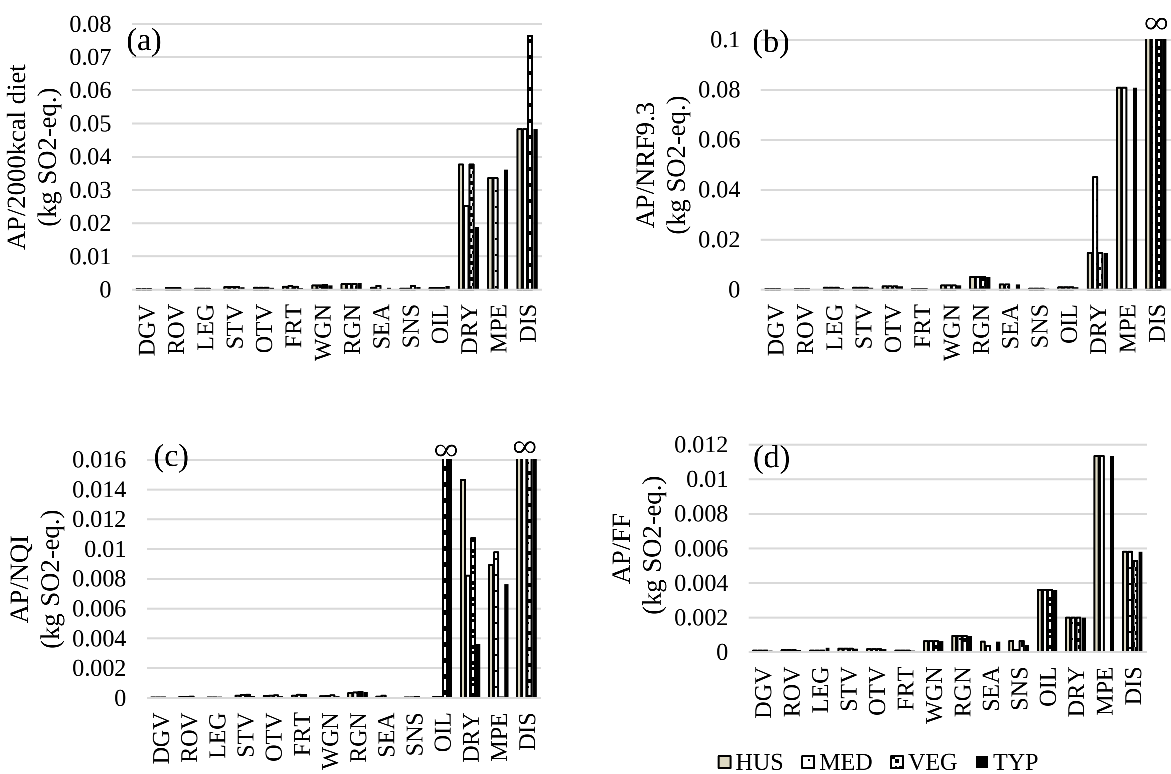


Figure 2.6. AP profiles of food categories in four dietary patterns within 2000 kcal daily consumption based on (a) mass, (b) NRF9.3, (c) NQI, and (d) FF.

Figure 2.6c shows that in the vegetarian and typical U.S. diets, oil generated a high NQI-based AP, mainly because of its negative NQI in both diets (Table 2.3). The vegetarian and typical U.S. food patterns had higher consumption of soy, nuts and seeds, and higher oil consumption, respectively, which provided more than enough qualifying nutrients primarily from lipids, such as vitamin E, resulting in their content of disqualifying nutrients outweighing their dietary need, signified by the negative NQI of these two categories. Dairy obtained lower NQI-based AP in the “typical” U.S. and Mediterranean diets than in the healthy U.S. and vegetarian diets due to increased importance of dietary calcium when less dairy is consumed. Meat, poultry, and eggs obtained their lowest NQI-based AP in the vegetarian diet due to limiting consumption to only eggs. The lower NQI-based AP of eggs compared with the meats consumed in the other diets was more due to the lower AP per mass of the eggs (approximately one-tenth that of an equivalent mass of beef) than on the egg’s NQI; as shown in Table 2.3, the mean NQI of eggs in the vegetarian diet was relatively low at 2.24.

Figure 2.6d indicates that meat, poultry and eggs, refined grains, oil, and dairy had, in the descending order, the highest AP when compared based on their satiety. Similar to the comparison based on other FU, these findings suggested that switching from refined grains to whole grains, or increasing the consumption of another source of carbohydrates, such as starchy vegetables, would improve the AP performance regardless of the diet.

Figure 2.7 demonstrates the EP- profiles of the four dietary patterns calculated using different FU. On the mass basis (Figure 2.7a), refined grains had the largest EP impact in the typical U.S. diet because of its higher consumption in this dietary pattern than other ones. Dairy was the next most important category for mass-based EP and produced a more significant impact in the healthy U.S. and vegetarian food patterns due to higher recommended dairy consumption.

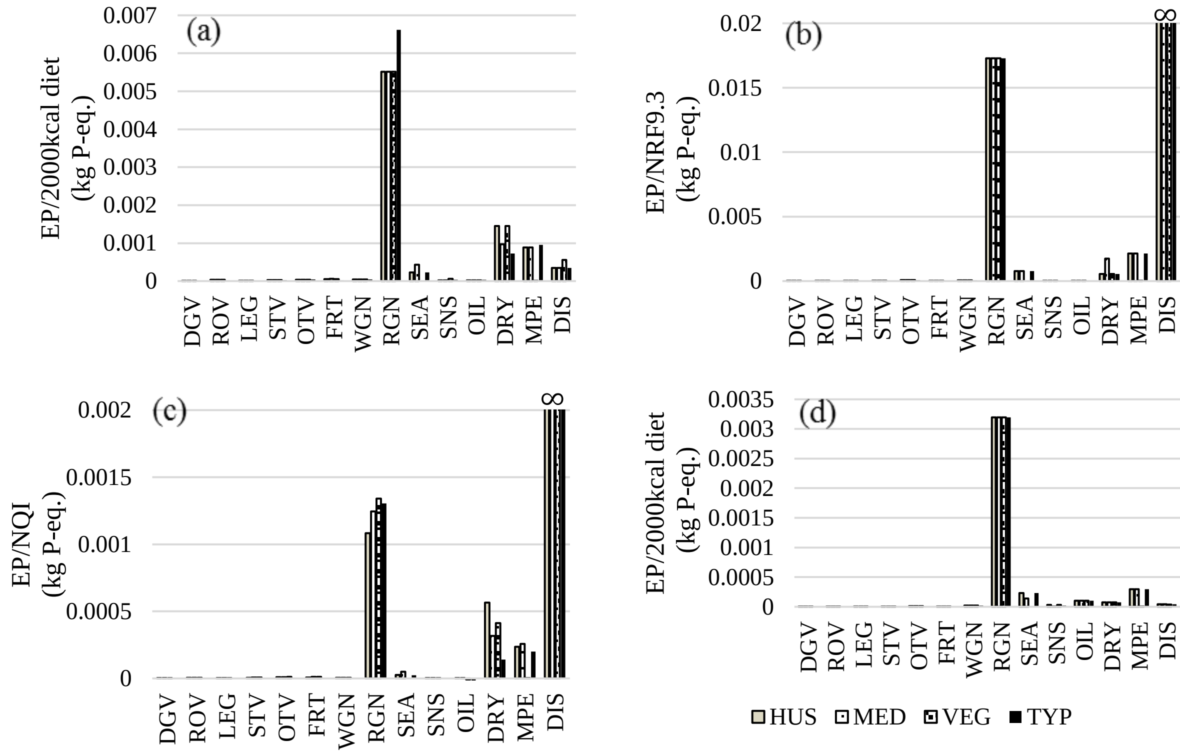


Figure 2.7. EP profiles of food categories in four dietary patterns within 2000 kcal daily consumption based on (a) mass, (b) NRF9.3, (c) NQI, and (d) FF.

For the NRF9.3-based EP (Figure 2.7b), the discretionary foods became the least sustainable by virtue of negative NRF9.3 value (Table 2.3), which implied that these foods should be removed from the diet to improve both nutritional quality and environmental performance. Refined grains were next in line and exhibited approximately three times the NRF9.3-based EP than on the mass-based value.

As shown in Figure 2.7c, due to the negative NQI value (Table 2.3), the NQI-based EP followed the profiles of GWP (Figure 2.3) and AP (Figure 2.6c), in which oil and discretionary foods exhibited infinitely high impacts. Refined grains had lower NQI score in the vegetarian diet (Table 2.3), so they appeared to show a slightly larger NQI-based EP. Similarly, dairy had lower NQI-based EP in the healthy U.S. diet due to higher consumption. As for the FF-based EP

(Figure 2.7d), refined grains exhibited the highest value, due to both their relatively low FF (Table 2.3) and higher EP impacts per mass unit (Figure 2.7a).

3.2 Environmental performance of example daily diets

3.2.1. Index values

Table 2.7 displays the NRF9.3, NQI, and FF values of selected food items for meals, which were shown in Table 2.2, served in a 2000-kcal example day according to different dietary patterns. The NRF9.3 and NQI of the example discretionary foods were always negative across diets, with the exception of the “unhealthy” U.S. diet, suggesting that in practice these diets could be improved by replacing the calories corresponding to discretionary foods with other sources, such as fruit or vegetables, or foods with high content of shortfall nutrients.

Table 2.7. The values of nutrient and satiety indices of selected foods in the example dietary patterns

Healthy U.S.				**Typical U.S.**			
	NRF9.3	NQI	FF		NRF9.3	NQI	FF
DGV-broccoli	0.3	30.3	0.5	DGV-broccoli	0.2	22.3	0.3
ROV-carrot	3.5	12.5	1.9	ROV-carrot	2.2	14.8	1.2
LEG-chickpeas	0.1	19.8	0.3	LEG-chickpeas	0.1	16.1	0.2
STV1-corn	0.1	9.4	0.5	STV1-corn	0.1	7.8	0.6
STV2-split peas	0.9	52.7	0.7	STV2-split peas	1.2	40.1	0.8
OTV-cucumber	0.4	33.4	1.1	OTV-cucumber	0.6	25.4	1.6
FRT-banana	0.8	11.1	4.1	FRT-banana	0.5	9.6	2.5
WGN 1-oats	0.3	36.8	0.4	WGN 1-oats	0.4	29.2	0.6
WGN 2-brown rice	0.0	6.5	0.4	WGN 2-brown rice	0.1	5.0	0.5
RGN-white bread	0.2	11.9	0.6	RGN-white bread	0.3	10.1	1.0
DRY-1% milk	0.9	5.8	10.3	DRY-1% milk	0.6	6.2	7.1
SEA-sardines	0.2	25.2	0.3	SEA-sardines	0.2	22.5	0.5
MPE-chicken	0.1	3.3	1.3	MPE-chicken	0.1	2.2	1.9
SNS-peanuts	0.2	42.1	0.1	SNS-peanuts	0.6	28.9	0.5

Table 2.7. continued

OIL-canola oil	0.5	19.6	0.1	OIL-canola oil	1.2	1.8	0.3
DIS-butter	-0.1	-11.2	0.1	DIS-butter	-0.1	-12.1	0.1
Mediterranean				**Vegetarian**			
	NRF9.3	NQI	FF		NRF9.3	NQI	FF
DGV-broccoli	0.5	14.6	1.1	DGV 1-leaf lettuce	0.1	20.6	0.1
ROV-tomato	0.7	6.3	4.4	DGV 2-broccoli	0.3	15.1	0.5
LEG-lentils	0.3	23.1	0.9	ROV-tomato	0.7	6.5	4.2
STV-potato	1.0	10.4	4.0	LEG-chickpeas	0.3	13.3	0.6
OTV 1-mushrooms	0.1	6.2	1.2	STV-corn	0.5	6.1	2.0
OTV 2-eggplant	0.0	4.2	0.9	OTV 1-cucumber	0.0	2.8	0.7
FRT 1-strawberries	1.2	7.6	4.9	OTV 2-onion	0.1	3.6	0.8
FRT 2-grapes	0.4	4.2	2.7	OTV 3-zucchini	0.1	5.8	0.8
FRT 3-orange	1.2	7.6	3.9	FRT 1-apple	0.2	3.3	2.9
WGN-brown rice	0.2	6.1	1.5	FRT 2-strawberry	1.2	8.3	4.7
RGN-pasta	0.2	7.3	1.4	WGN 1-oats	0.6	21.8	0.9
DRY-yogurt	0.7	0.2	11.6	WGN 2-brown rice	0.1	3.2	0.7
DRY 2-mozzarella cheese	1.0	-3.1	4.1	RGN-white bread	0.3	4.8	1.1
SEA1-sardines	0.3	13.7	0.6	DRY 1-cheddar cheese	0.8	-0.4	2.1
SEA 2-salmon	0.2	10.0	0.7	DRY 2-mozzarella cheese	0.5	0.0	1.9
MPE-chicken	0.2	2.6	2.6	DRY 3-yogurt	0.3	1.1	5.5
SNS-almonds	0.9	68.3	0.4	MPE-eggs	0.0	3.6	0.2
OIL-olive oil	0.3	6.0	0.1	SNS 1-almonds	1.7	38.0	0.7
DIS-butter	-0.7	-28.2	0.4	SNS 2-peanuts	0.7	21.3	0.5
				OIL-olive oil	0.1	1.7	0.0
				DIS-butter	-0.1	-15.3	0.1

Unhealthy U.S.

	NRF9.3	NQI	FF
ROV-tomato	0.2	210.1	1.3
STV-potato	0.3	181.9	1.3
MPE 1-eggs	0.1	22.3	0.6
DRY 1-cheddar cheese	0.7	11.0	1.9
DRY 2-ice cream	0.3	26.3	1.5
RGN-white bread	0.3	33.3	0.9
DIS 1-butter	-0.1	-3.5	0.1
DIS 2-soda	-0.5	-2.5	14.5

Table 2.7. continued

DIS 3- pepperoni pizza	1.1	29.0	5.0
DIS 4-cheeseburger	0.3	27.7	2.5

Figure 2.8 shows the calorie composition of an example 2000-kcal "unhealthy" U.S. diet, which demonstrated well the importance of dietary context for the NQI. The 2000 kcal energy requirement of the diet was dominated by pizza consumption (approximately one-third), even though the corresponding amount of calories represented only two slices of pepperoni pizza.

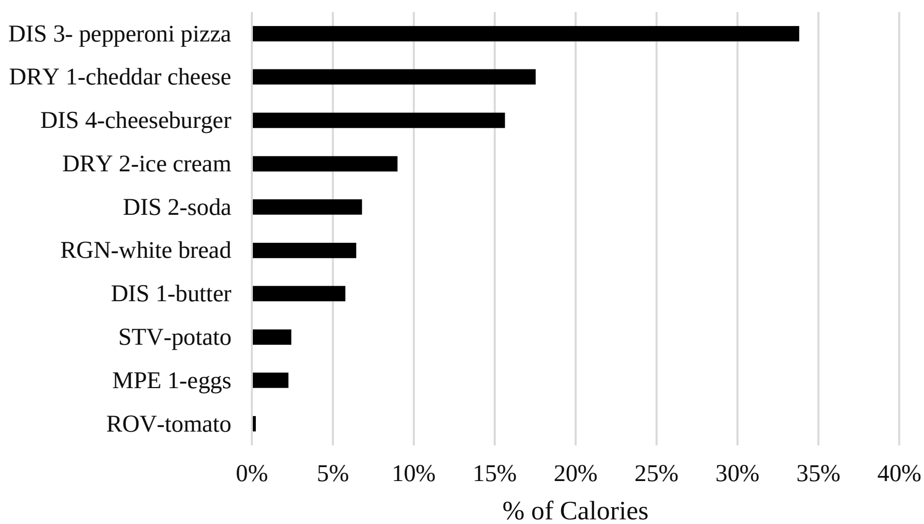


Figure 2.8. Calorie composition of an example 2000-kcal unhealthy U.S. diet.

Table 2.8 shows the example "unhealthy" U.S. diet constructed from low nutrient density, high energy foods, which poorly met the nutritional requirements, even when the total calorie intake was controlled at 2000 kcal. There were highly insufficient intakes of dietary fiber, vitamins C and E, magnesium, and potassium, and significant surplus of saturated fat and sodium.

Table 2.8. Daily intake, RDV/MRV and consumption ratio in the example unhealthy U.S. diet

	Total daily intake	**RDV/MRV**	**Consumption ratio**
Prot. (g)	78.5	88	89%
Dietary fiber. (g)	7.5	30	25%
Saturated fat (g)	51.2	27	190%
vit. A (ug)	821.3	700	117%
vit. C (mg)	9.7	75	13%
vit. E (mg)	4.1	8	52%
Calcium (mg)	1425.8	800	178%
Fe (mg)	11.6	9	129%
Mg (mg)	149.3	280	53%
K (mg)	1306.2	3100	42%
Na (mg)	3526.1	2400	147%
Added sugar (g)	54.8	59	93%

3.2.2 GWP

Figure 2.9 shows the GWP profiles of five example diets calculated using different FU. It is seen in the healthy U.S. food pattern (Figure 2.9a) that the selected dairy (1% milk) exhibited the highest mass-based GWP but became more environmentally sustainable when its nutrient quality was considered. For the NRF9.3-based GWP, the discretionary food (butter) and chicken exhibited the highest values. However, chicken had lower GWP based on NQI, because it was the primary source of protein in this example day of eating following the healthy U.S. food pattern. Oil and butter both contributed higher FF-based GWP due to their high energy density, which resulted in lower satiety contribution per consumed portion of food.

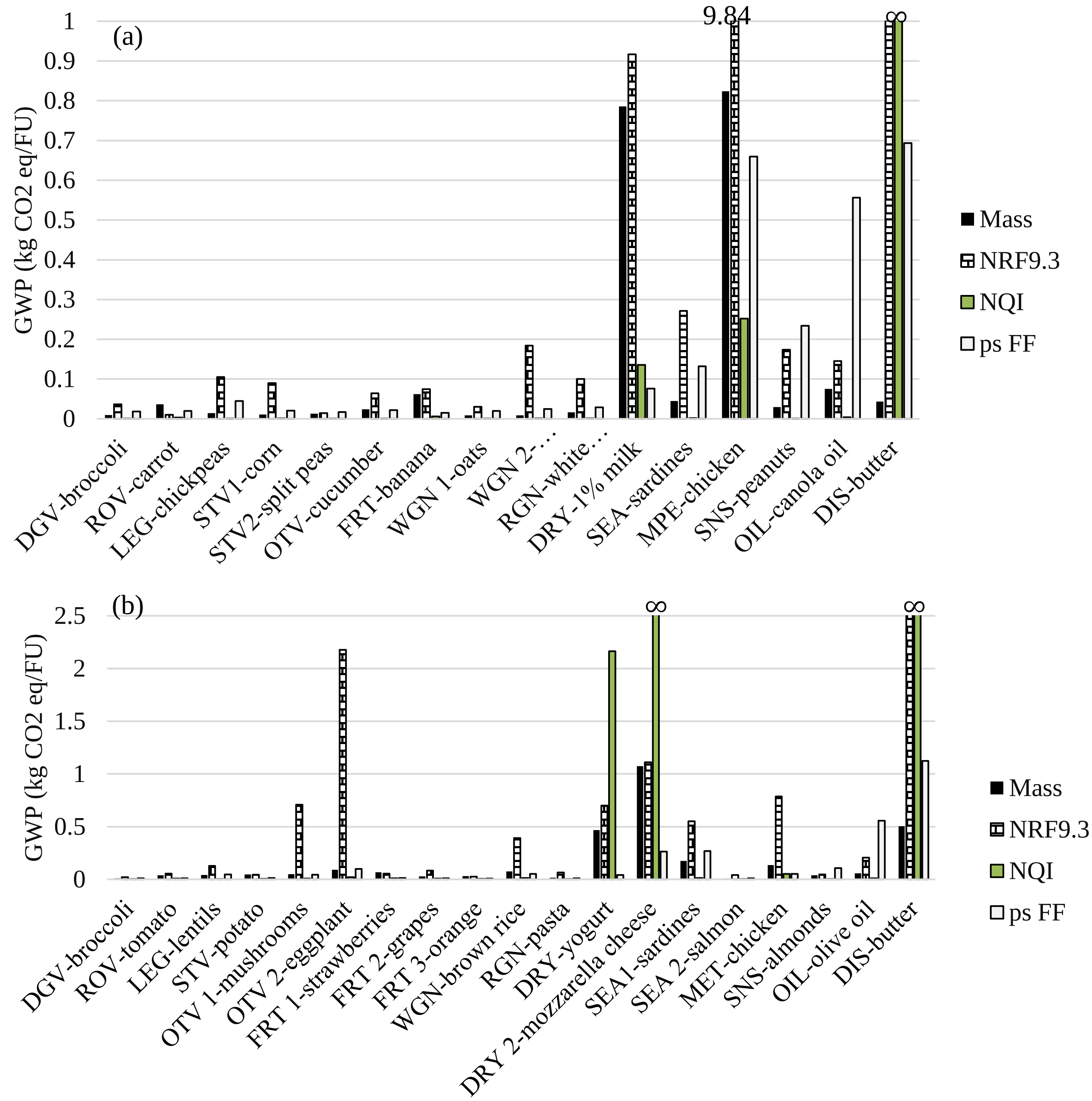
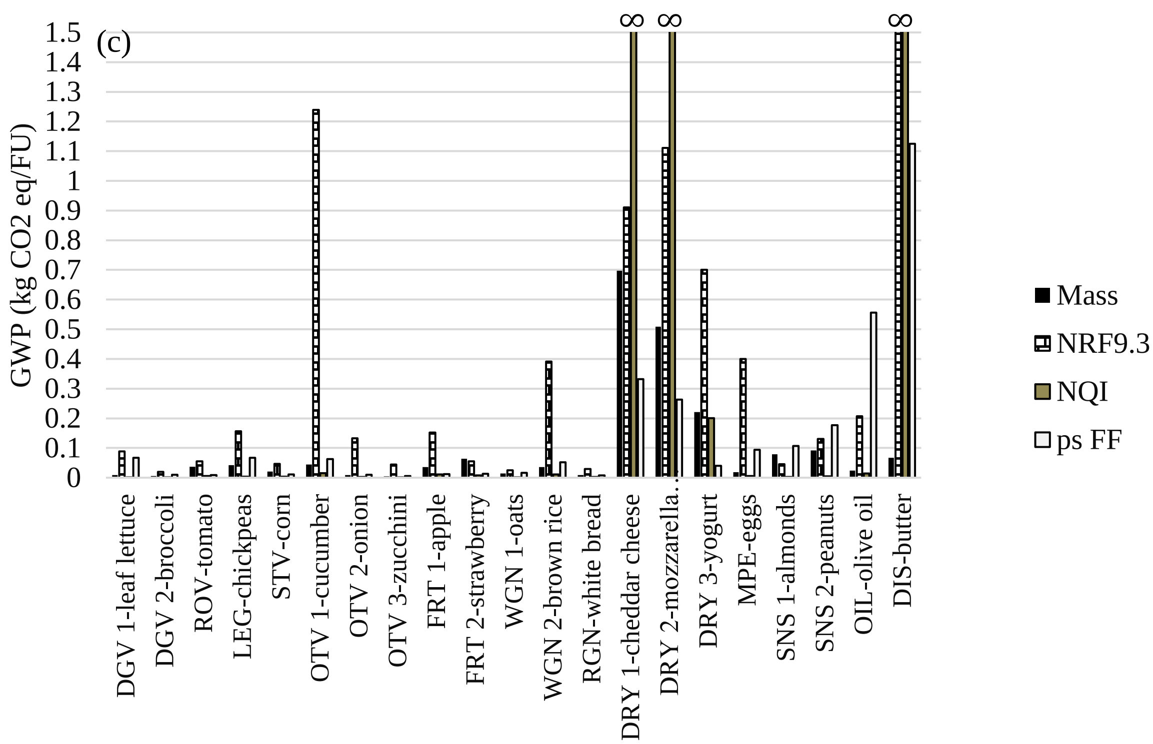


Figure 2.9. GWP profiles of example (a) healthy U.S., (b) Mediterranean, (c) vegetarian, (d) typical U.S., and (e) unhealthy U.S. diets based on different FU.

Figure 2.9. continued



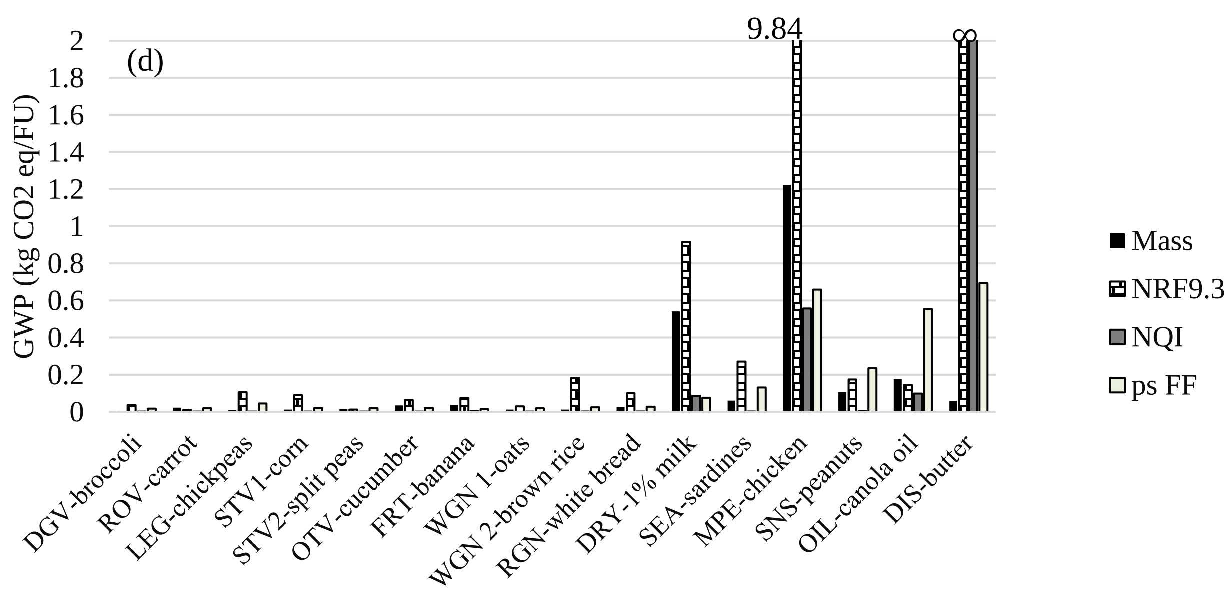
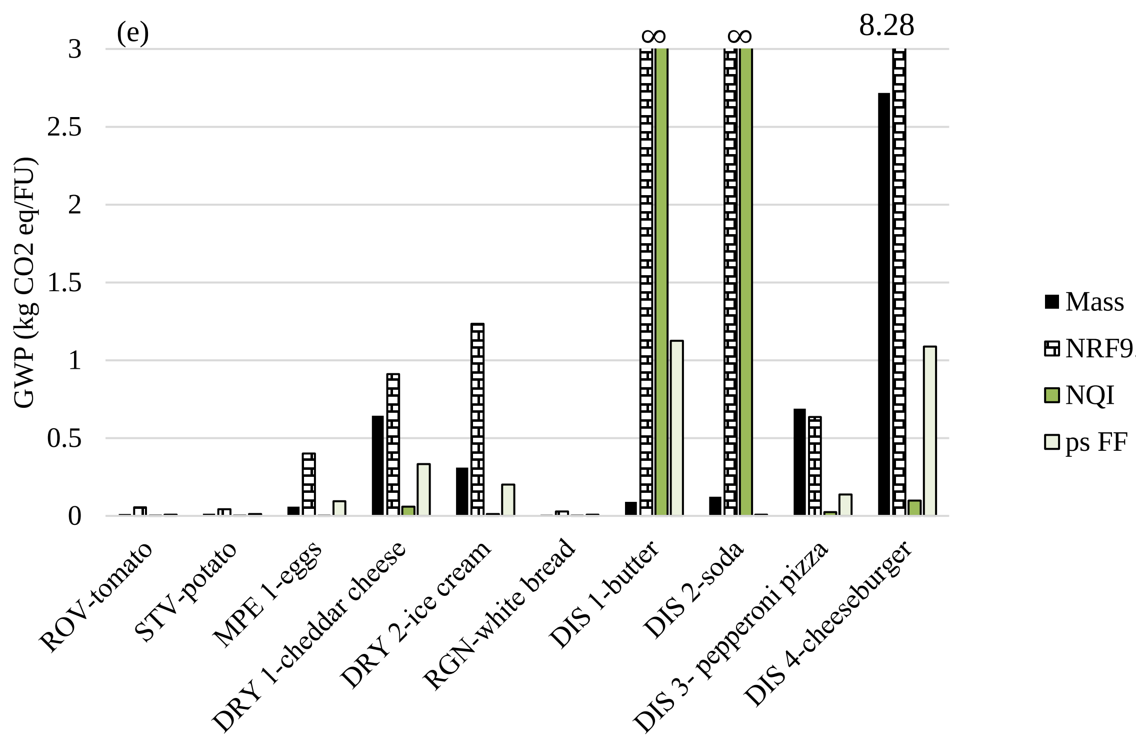


Figure 2.9. continued



In the Mediterranean dietary pattern (Figure 2.9b), the selected dairy foods (yogurt and mozzarella cheese), discretionary foods (butter), and chicken contributed the highest mass-based GWP. Yogurt exhibited a lower NRF9.3-based GWP than chicken. Mushrooms and eggplant showed noticeably higher GWP on the basis of NRF9.3 than the other FU; their NRF9.3-based GWP were also noticeably higher than the selected foods from the fruit and vegetable categories accompanied in the diet. On the NQI basis, the butter and mozzarella cheese should be removed from the diet to improve the nutritional and environmental performance. As to the FF-based GWP, butter and oil, followed by sardines, mozzarella cheese and almonds exhibited the highest values, due to their high energy and resulting lower satiety.

In the example vegetarian food pattern, as shown in Figure 2.9c, the GWP was significantly higher for dairy foods on the basis of mass than FF, and cheeses had infinitely high NQI-based GWP because of their negative NQI values (Table 2.3). Broccoli outperformed leaf lettuce in terms of NRF9.3-based and FF-based GWP. Cucumber, which has high water content and consequently low energy and nutrient density, exhibited higher NRF9.3-based GWP than any other food items in this example diet except for butter. Brown rice showed higher NRF9.3- based GWP than white bread, and starchy vegetable (corn) which could also be considered as an alternative carbohydrate source. In this example diet, regardless of the FU, oats, as the other source of whole grain, had a better environmental performance than brown rice, especially on the NRF9.3 basis. Similar to previous example diets, high lipid-containing foods (butter, olive oil, peanuts and almonds, and eggs in the descending order) had higher FF-based GWP due to their high energy density.

Comparing the “typical” U.S. diet (Figure 2.9d) with healthy U.S. diet (Figure 2.9a), the changes in the GWP profiles were observed when the proportions of the food categories within a diet were shifted, even though all the selected food items remained the same. The changes in the GWP of the vegetable and grain categories were minimal. However, the increased meat, poultry and eggs consumption in the “typical” U.S. diet resulted in higher mass- and NQI-based GWP, respectively because increased amount of chicken was consumed, and the nutrient (protein) quality that chicken contributed to this diet was lower (i.e., lower NQI). The selected dairy food (1% milk) exhibited lower GWP on all FU bases in the “typical” U.S. diet compared with the healthy U.S. one because of lower consumption.

For the GWP profile of the “unhealthy” U.S. diet, as shown in Figure 2.9e, the selected vegetable and grain had lower GWP than other categories regardless of the FU. Cheddar cheese and ice cream performed significantly better on the basis of NQI than the others in this example dietary context due to their higher contents of shortfall nutrients. For example, ice cream accounted for approximately 25% of the potassium content of this diet, which is a significant shortfall nutrient, with a consumption ratio of only 42% of the RDV. Butter and soda possessed negative NRF9.3 and NQI scores, which were responsible for their infinitely high NRF9.3- and NQI-based GWP. Despite their significant contents of disqualifying nutrients, including saturated fat and sodium, pepperoni pizza and cheeseburger had significantly better environmental performance based on NQI than mass and NRF9.3 due to their contributions to protein, dietary fiber, and qualifying micronutrients, including vitamins A and E, calcium, iron, magnesium, and potassium.

Table 2.9 shows the total GWP of the five example diets calculated using different FU. It is apparent that the largest mass was consumed in the "unhealthy" U.S. example, followed by the Mediterranean, and Vegetarian examples. Although many of the foods included in the "unhealthy" U.S. example are energy dense, suggesting that the "unhealthy" U.S. diet should result in the lowest food mass consumed, the large mass (368 g) of high water content cola soft drink included in this diet contributed to this somewhat unexpected result. The mass of the healthy U.S. and "typical" U.S. examples were considerably lower than the mean possible when foods are selected according to their dietary patterns (Table 2.4). The mass based GWP of the "unhealthy" U.S. example was more than double that of the healthy U.S. and vegetarian examples. The NRF9.3 based GWP of the "unhealthy" U.S. example was more than seven times that of the healthy U.S. example, which exhibited the lowest NRF9.3 based GWP, although similar values were obtained by all the example diets with the exception of the "unhealthy" U.S. example. The total NQI-based GWP was highest for the Mediterranean example and lowest for the healthy U.S. example. The "unhealthy" U.S. example resulted in relatively low NQI-based GWP due to its high total NQI that resulted from low consumption ratios in several qualifying nutrients (Table 2.8). The total FF-based GWP was lowest for the Mediterranean example and highest for the “unhealthy” U.S. example.

Table 2.9. Mean values of total mass and total GWP of the example diets scaled by different FU on a 2000 kcal basis

Dietary pattern	**Total food mass (g)**	**Total GWP-mass in diet (kg CO_2 eq.)**	**Total GWP-NRF9.3 (kg CO_2 eq./NRF9.3)**	**Total mean GWP-NQI (kg CO_2 eq./NQI)**	**Total GWP-FF (kg CO_2 eq./ FF)**
HUS	733.8	2.01	0.241	0.006	0.088
MED	1590.1	2.95	0.339	0.018	0.062
VEG	1019.5	2.04	0.244	0.012	0.065
TYP	698.4	2.36	0.285	0.010	0.120
“U”HUS	1777.3	4.67	1.732	0.009	0.157

4. Discussion

This study has addressed the current research gaps that were identified by Hallström et al. in their systematic review of the use of dietary quality scores in assessments of the sustainability of food products and human diets (Hallström et al., 2018). To establish a wider perspective of the environmental profile of dietary patterns, in addition to global warming which was commonly reported in literature, this study examined the acidification and eutrophication of total of seventy-four food items (Table 2.1). Regardless the FU applied, the results showed that refined grains can be less environmentally sustainable than meat products. This finding also highlights the importance of the geographic distribution of environmental impacts associated with food production, as the freshwater eutrophication occurs specifically in the location where the food is grown and harvested due to agricultural practices such as fertilization, irrigation and pest management (Larsson & Granstedt, 2010). Even grains have different levels of impacts; for example, growing rice results in considerably higher eutrophication and acidification than barley, oats and wheat (M. Wang, Xia, Zhang, & Liu, 2010; Wernet et al., 2016). As to the production of animal-based foods, more life cycle stages are involved which can generate emissions due to farming of feed ingredients and raising of animals (Wernet et al., 2016). For meat and poultry, a large amount of waste is also generated during animal production such as viscera and meat scraps from slaughtered animals (Asem-Hiablie et al., 2019). Dairy products such as cheese and yogurt cause high environmental burdens due to the need for large quantities of milk and the energy use associated with food processing such as pasteurization and cheesemaking (Jong, 2013).

The Dietary Guidelines for Americans provides considerable flexibility for personal preference within the framework of meeting the intakes of each category and subcategory. The guidelines encourage shifting to more nutrient-dense foods, with the goal of increasing public health and reducing chronic disease incidence. The nutrient density of food has been quantitatively addressed in many studies through nutrient profiling and the development of nutrient quality indicators such as the NRF9.3 and NQI (Hallström et al., 2018). Addressing the need identified by Hallström et al. to include dietary context in assessments of food sustainability, example daily diets were constructed in the study using the food patterns recommended in the Dietary Guidelines for Americans, as well as typical American and an example of unhealthy American diet. Additionally, the NQI was specifically designed as a score that reflects the nutrient quality of individual food item in a dietary context (Sonesson et al., 2019), and its usability has been further explored in this study. The wide range of NQI obtained from the same category of foods (Table 2.3) demonstrated the importance of dietary context for both nutritional and environmental performance. For example, ice cream, in general considered as an unhealthy food, can still be nutritionally valuable if its accompanying foods in the dietary context are poor in terms of ratio and amount of qualifying and disqualifying nutrients (Figure 2.9e).

The applications of nutrition-based FU in food LCA have been demonstrated, which included food commodities of major economic importance and high consumer acceptability in the U.S. Key findings that are expected to help guide the decision-making of the U.S. consumers, food manufactures and policy makers include: (1) the importance of considering the environmental performance of a particular food item, instead of just a broad food category, as evidenced by the large variation observed in the midpoint impact results; (2) vegetarian diet can deliver comparable nutritional quality in terms of the nutrients considered in the NRF9.3 (Eq. 1) at comparable or reduced environmental cost, as evidenced by its consistently lower mean value of midpoint impacts; (3) discretionary, leeway, or junk foods should be minimized to improve both human health and environmental sustainability (Table 2.3, Figures 2.1, 2.2, 2.3 and 2.8), as they provide limited nutritional benefits and adversely impact the environment in several categories. The discretionary foods selected in this study are commonplace, popular and affordable, however, they exhibit low nutrient density and thus poor environmental performance on the bases of nutritional FU. Overconsumption of these foods has been associated with chronic disease risk (WHO, 2002). Animal food products, including meat, poultry and eggs, dairy, and animal-based discretionary were also identified as environmental hotspots, which agreed with previous LCA studies on both American and European dietary contexts (Drewnowski et al., 2015; Heller & Keoleian, 2015; Perignon et al., 2016; Sturtewagen et al., 2016; Van Kernebeek et al., 2014; Werner, Flysjö, & Tholstrup, 2014). Minimizing the consumption of these foods to the levels recommended to maintain human health will likely improve the environmental performance of dietary patterns. Starchy vegetables are recommended to be eaten in place of refined grains as the source of carbohydrate to minimize terrestrial acidification. However, due to the wide range of the results, Mediterranean and vegetarian diets are not necessary superior to typical U.S. and healthy U.S. diets in terms of nutritional quality, satiety and environmental sustainability, unless they are carefully constructed with the aim of co-optimizing these dimensions.

While all the results presented in Section 3 were calculated based on constant daily energy intake, of 2000 kcal, the environmental footprints of dietary patterns are expected to be closely related to how many calories are consumed per day. A sensitivity analysis was conducted, and Figure 2.10 demonstrates the effect of total daily calorie consumption on the carbon footprint of correspondingly scaled dietary patterns. Higher calorie diets resulted in higher dietary carbon footprint. There was relatively small difference among the values and trends of the healthy U.S., Mediterranean, and typical U.S. diets, but the vegetarian diet exhibited consistently lower mass-based GWP than the others. The average observed increase in GWP per additional calorie was 0.0026 kg CO_2-eq., although in practice it is mainly determined by the food selected due to the large variation in the energy densities of different foods. According to the Food and Agriculture Organization of the United Nations, the average American takes approximately 3,600 calories per day (FAOSTAT, 2019). While there are individuals in the population who do require this much energy for sustenance, 3600 kcal represents an energy surplus that is both unnecessary and unhealthy for an average person, and unsustainable for the environment. High satiety foods can help prevent overconsumption and thus improve the dietary environmental footprint.

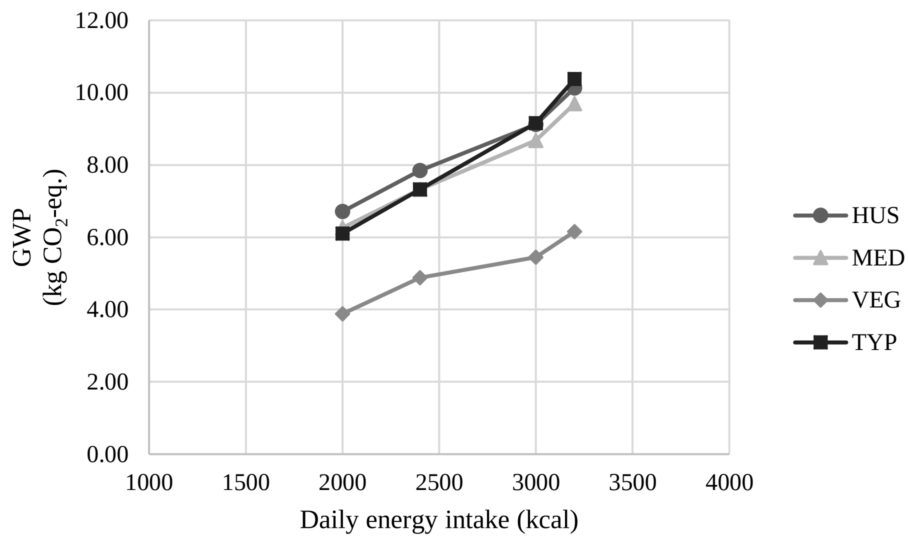


Figure 2.40. The effect of daily energy intake on the GWP of different dietary patterns.

As presented in Table 2.4, this study found that the mean GWP of four U.S. dietary patterns (per 2000 kcal day) ranged from 3.88 to 6.71 kg CO_2 eq. These values are of similar magnitude to the GWP per daily diet identified in the UK, of 5.60 and 6.71 kg CO_2 eq. per 2126 and 2094 kcal diets, respectively, in accordance to the Dietary Approaches to Stop Hypertension (DASH) dietary pattern (Monsivais et al., 2015). This UK-based study assessed the diets of adults aged 39−79 y (n = 24,293) and calculated the GWP of 289 food choices. The lower value of 5.60 kg CO_2 eq. was associated with reduced consumption of meat and increased consumption of whole grains, which accords with one of the main trends identified here that abstinence from red meat in particular results in lower GWP (Section 3.1.2; Table 2.5). Like the current study, an GWP assessment of daily diet conducted in Australia (n = 9,341 adults) identified high variation depending on food choice, but this assessment also showed higher mean GWP values, of 18.72 ± 12.06 kg CO_2 eq. for males and 13.73 ± 8.72 kg CO_2 eq. for females, which was due to much higher energy intakes than this study, ranging to higher than 6000 kcal (Gilly et al., 2016). Therefore, the Australian results are consistent with the trend observed in our sensitivity analysis

(Figure 2.10) that dietary pattern with higher daily energy intake results in higher GWP. In the Australian dietary context, meat and discretionary foods (including processed meat, burgers, tacos and pizza) were also shown to be the hotspots of GHG emissions, accounting for 33.9% and 29.4% of the total dietary GWP, respectively. The mean GWP per daily diet observed in the French population (n = 2,624; aged > 18 years) was 4.896 and 3.667 kg CO_2 eq. for men and women, respectively, with an overall mean energy intake of 2,128 kcal (Perignon et al., 2016). These results were based on 402 foods and are also of comparable magnitude to those of the current study. Possible reductions in GWP via dietary shifts were similarly identified by increasing the proportions of fruit and vegetable consumption and reducing consumption of ruminant meats.

The limitations of this study include: (1) the complexity and heterogeneity of food production chains; (2) the effect of food safety; and (3) other important nutrients, specifically for vegetarians and vegans, that are not included in the NRF9.3 and NQI calculations, such as B vitamins. In the LCA conducted this study, wherever possible the most current global or U.S. data were used. However, the life cycles of food commodities could be geographically heterogeneous in a country as large as the U.S. due to the variations in climate, soil condition and thus farming practice. Food safety is a global concern that causes potential risk to public health, however, has received little attention in the food LCA studies. For example, fresh vegetables, especially leafy greens are associated with a large number of food outbreaks, which not only damage human health but also result in significant loss of food products and compounding the environmental burdens. The large variation associated with even a small set of foods selected in this study compared with the options available in market to consumer shows that the vegetarian and Mediterranean food patterns cannot reasonably be considered always more environmentally sustainable than the healthy and typical U.S. ones. To improve the environmental performance of a diet without compromising its nutritional quality and satiety, an appropriate selection of food items in the diet is critical, because a single food item can be considered more or less sustainable depending on both its primary function (e.g., mass, source of nutrients, or source of satiety) and the accompanying foods in the diet. Moreover, in addition to causing burdens to environment, the impacts of less sustainable foods could further damage human health and longevity. Therefore, further studies are needed to examine the net consequence considering both the nutritional health benefits and environmental health damages associated with dietary choice.

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CONCLUSIONS AND FUTURE WORK

Conclusions

This thesis has evaluated the environmental sustainability of upstream agricultural production and downstream food consumption through a life cycle approach. The first part compared the life cycle impacts of fresh imported and frozen domestic organic blueberries consumed in Indiana. The second part evaluated the environmental performance of American dietary patterns from nutrition and satiety perspectives. Overall, key findings include: (1) Production and consumption of agri-food products can cause significant impacts on the environment, and their life cycle impacts associated with farming, processing, transportation, retail and consumption can be reduced by implementing appropriate practices and choices; (2) The life cycles of fresh produce are complex, in which both seasonality and locality play important roles in its environmental performance; (3) The environmental sustainability of organic blueberries is sensitive to multiple factors that include local farming practices and yield, transportation distance, periods of cold storage, and the type of refrigerant utilized; (4) The environmental profile of a dietary context depends not only on the food categories included, but more importantly, on the particular foods selected from each category; (5) Sustainable diets, in terms of high nutritional quality and low environmental footprint, should include a greater proportion of fruit and vegetables and a lower proportion of animal-based foods.

Future work

Sustainable development is defined as balancing local and global efforts to protect the natural environment with the fulfillment of basic human needs (Kates et al., 2005). Therefore, in addition to environmental protection, the sustainable development goals identified by the 2005

World Summit include economic and social developments (United Nations General Assembly, 2005). However, conducting an LCA in practical scenarios, whether focusing on upstream production or downstream consumption, requires simplifying product life cycles to their measurable and important components (i.e., unit processes) only. As defined in the scope and system boundaries, certain assumptions and cut-offs of reference flows are needed due to data availability and limitation in characterization models. Hence, it is necessary to consider whether some of the aspects that are not commonly incorporated in LCA studies on agri-food production and consumption today could be further investigated in future work. Such considerations of current research gaps are given in the following sections.

Improvement of LCA data availability and quality

Implementation of sustainability into food and public health policy, such as new Dietary Guidelines for Americans, or application of taxes on low sustainability foods, is difficult due to the large variation in the LCA data on foods, especially when they are produced and consumed in different regions of a country, particularly one as large and geographically heterogeneous as the U.S. Therefore, additional work is needed to improve both the availability and consistency of data on many different commodity and mixed food products, with equivalent system boundaries.

Food safety

Foodborne illness can have a catastrophic impact on all the aspects of sustainability in the event of outbreaks and recalls. The U.S. has one of the safest food supplies in the world due to tight regulations, but even so, according to the USDA ERS the annual economic cost associated with foodborne illness in the U.S. is higher than $15.6 billion (USDA, ERS 2017). According to the USDA Food Safety and Inspection Service, the total mass of food recalled in 2018 was approximately 9,322,644 kg, including approximately 5,980,871 kg of beef products primarily due to contaminations associated with *E. coli*, *Listeria*, and *Salmonella* (USDA, FSIS 2019). In addition to the damages to public health and society's economy, food waste due to recalls can generate great environmental impacts. Therefore, more insights into the effect of food safety on the sustainability of agri-food production are needed.

Food preservation and shelf-life extension

Foods generally rapidly decay in terms of sensory attributes and microbial safety. These deteriorations usually occur at the end-of-life cycle stages as food, especially climacteric produce (Murmu & Mishra, 2018), sits on grocery store shelves, in refrigerators and kitchen cabinets, resulting in severe food waste problem with detrimental impacts both economically and environmentally. Therefore, appropriate preservation technologies are needed to prolong food shelf-life, such as thermal processing or other novel techniques (e.g., nano-packaging). While emerging food processing technologies have been designed to preserve more nutrients or use less energy, their environmental sustainability is an interesting question for future work. Several studies have been conducted to address this question (Aganovic et al., 2017; Pardo & Zufía, 2012; Sampedro, McAloon, Yee, Fan, & Geveke, 2014); however, they have been limited by a lack of data on industrial production scale. High pressure processing was found with only little environmental benefits compared to thermal food preservation technology due to the significant emissions associated with the manufacture and procurement of its processing systems.

Food processing can, however, decrease the concentrations of heat labile nutrients, including vitamin C, vitamin A and some B vitamins (Ling, Tang, Kong, Mitcham, & Wang, 2015; Lund, 1977), and thus the nutritional value of food. The lower nutritional quality will increase the life cycle footprint of food when it is calculated based on nutritionally based FUs.

Furthermore, food preservation can cause additional environmental burdens due to the required consumptions of energy and/or chemicals. Hence, this complex interconnection among food processing, shelf life and nutritional value should be considered and further studied in future work in order to advance the framework of food LCA.

Nutrient bioavailability

The nutrition function of a food depends on the bioavailability of its nutrients, which is impacted by the food matrix and the processing applied. Several studies have shown the effect of particle size reduction of food by refining or thermal processing on the bioavailability of nutrients (Bakir, 2012; Carbonell- Capella, Buniowska, Barba, Esteve, & Frígola, 2014; Lipkie, 2014). Bioavailability is important for considerations of protein quality, such as the Protein Digestibility Corrected Amino Acid Score (PDCAAS), which has been utilized as FU in food LCA (Sonesson et al., 2017). However, the qualities of other macronutrients like carbohydrate and lipid, such as the proportion and types of dietary fiber and glycemic index response, and the concentration of unsaturated (particularly omega-3) fatty acids, respectively, have not been incorporated in to food LCA. Their bioavailability should be considered in future work in order to define more appropriate FUs for better assessing the environmental performance of carbohydrate and lipid-based foods.

Sensory enjoyment of food

Some research suggests the physical and mental health benefits of enjoyable activities (Downward & Dawson, 2015), including eating delicious foods. In fact, the enjoyment of food is one of its functions and taste is the primary driver of food purchases in the U.S. (Fatka, 2018), which has significant socio-economic importance. Pleasurable eating experiences are highly related to the perceived food quality (Sneijder & te Molder, 2006), for example the "tender" and "juicy" texture (Brown, Gerault, & Wakeling, 1996) of beef and pork determined by their intramuscular fat content. However, this function of food has not been incorporated in food LCA because of its inherent subjectivity. With better quantification techniques of food sensory attributes, new FUs can be defined and applied in food LCA.

Consumer behavior

The last life cycle stage of food before becoming human excrement (Ghinea et al., 2014), being disposed (Arvanitoyannis, 2008), or recycled is consumption, in which consumer behavior plays a crucial role. For example, consumption of food at home or away from home will likely cause disparate environmental impacts. This idea was assessed in a Belgian context by Sturtewagen et al, who found that in comparison with the same food eaten at home, the food eaten in a cafeteria had lower environmental impacts due to greater efficiencies associated with storage and preparation of food en masse (Sturtewagen et al., 2016). In an American context, it is often the case that excessive calories are consumed away from home, with lower proportion of fruit and vegetables in meal, resulting in higher public health and environmental burdens than food consumed at home (Todd, 2010). Furthermore, consumer behavior is the key aspect determining the amount of food waste generated, which needs to be better characterized in order to refine food LCA studies.

Consumer-friendly access to LCA results

Since many consumers do not read LCA-related publications, they could directly benefit from LCA work if the key findings are incorporated into user-friendly smart applications. The development of easy to use internet and smartphone applications that incorporate nutrition, price, and sustainability dimensions of food could greatly facilitate adoption of more sustainable dietary patterns by consumers (Sonesson et al., 2019). This tool would be especially useful when

NQI-based environmental footprint is considered due to the importance of dietary context, instead of nutritional quality of particular foods, to the overall nutritional performance, Although such an application could be launched by currently existing technology, accurate LCA data on more foods is needed.

Economic sustainability

The sustainability of a food production chain should consider not only its environmental and social impacts, but also economic performance. The affordability and price elasticity of demand associated with food are important to the behaviors of consumers and suppliers. For instance, healthier eating habits through dietary shifts to consume more fruit and vegetables could result in their significant price increases, thus decreasing the affordability of these foods for some of the population, especially the consumers with lower income. This indirect (secondary) economic effect should also be considered when designing a more sustainable production chain.

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