RESEARCH REPORT

ENVIRONMENT

Title: A Comparative Life Cycle Assessment of Calorically Equivalent Meals with and without Pork – **NPB #16-124**

Investigator: Greg Thoma

Institution: University of Arkansas

Co-Investigators: Ben Putman
Daesoo Kim
Kelli Young

Date Submitted: January 2019

For more information contact:

National Pork Board • PO Box 9114 • Des Moines, IA 50306 USA • 800-456-7675 • Fax: 515-223-2646 • pork.org

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List of Acronyms

ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
BEA	Bureau of Economic Analysis
BTS	Bureau of Transportation Statistics
CCP	Current Food Consumption Patterns
CEDA	Comprehensive Environmental Data Archive
CNPP	Center for Nutrition Policy and Promotion
CO2	Carbon Dioxide
CV	Coefficient of Variation
DALYs	Disability Adjusted Life Years
EIO-LCA	Economic Input-Output Life Cycle Assessment
ERS	Economic Research Service
FP	Food Patterns
FPED	Food Pattern Equivalents Database
GHG	Greenhouse Gas
GHGE	Greenhouse Gas Emission
GWP	Global Warming Potential
LAFA	Loss-Adjusted Food Availability
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MCS	Monte Carlo Simulation
MSW	Municipal Solid Waste
MT	Million Tons
NADA	National Automobile Dealers Association
NAICS	North American Industry Classification System
NHANES	National Health and Nutrition Examination Survey
NPB	National Pork Board
NRDC	Natural Resources Defence Council
RCP	Recommended Food Consumption Patterns
RITA	Research and Innovative Technology Administration
SD	Standard Deviation
USDA	United States Department of Agriculture
USDOC	United States Department of Commerce
USEPA	United States Environmental Protection Agency

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Executive Summary

1 Introduction

Increasing awareness of environmental and health issues related to food production, distribution, and consumption has led to studies focused on understanding the connection between nutritionally sound consumption and potential environmental impacts. One area of focus has been in swine production. Continued profitability of the swine production sector depends on producers understanding how consumers consider sustainability and nutrition when purchasing, preparing and consuming pork. The main objective of this project was to perform a comparative life cycle assessment (LCA) of greenhouse gas emissions (GHGEs), land use, and water use for pork and pork-free alternative diets/meals that are nutritionally equivalent. We included a diet level comparative evaluation of USDA current consumption patterns (CCP) and recommended consumption patterns (RCP). The study specifically accounted for different rates of food loss in the supply chain for each component of the diets/meals.

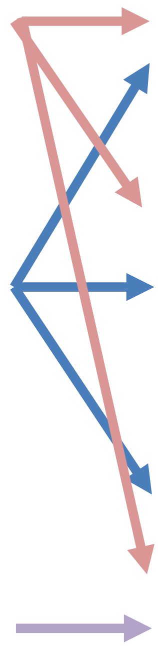
A comprehensive review of the literature and industry reports was performed to identify relevant lifecycle inventory (LCI) information for environmental and nutritional impacts. The literature review focused on two methodological requirements: (1) LCI for typical recommended U.S. diets/meals and the nutrient profiles of their ingredients and (2) the inclusion of nutritional characteristics as part either of the functional unit (enforcing iso-caloric comparisons) or as contributing factor to the impact on health by incorporation of diet-health relationships in the impact assessment. This LCA is a comparative field-to-fork (or cradle-to-grave) assessment of the production, distribution, and consumption of diets/meals containing pork, and nutritionally equivalent (iso-caloric) alternatives consumed in the U.S. The primary audience for this LCA is the swine production industry to be used for internal decision-making purposes.

2 LCA Methods

The goal of the LCA is to compare the potential environmental and health impacts associated with the production and consumption of diets/meals that include pork versus nutritionally equivalent diets/meals without pork, as outlined in Table ES 1. This study considered both dietary and single meal scenarios. The environmental indicators evaluated include global warming potential (GWP), land use, and water use. Two alternate functional units for the LCA were defined: 1) the average daily food consumption derived from estimated annual consumption at

Table ES 1. Scenarios evaluated. The first three data sources were used as the basis for three alternate dietary scenarios (arrows indicate the nine resulting scenarios). 6 meal scenarios are also included in the study.

Dietary data source	**Description**		**Alternate Scenarios**	**Symbol**
USDA Dietary Guidelines	The current consumption pattern (CCP) (Usual US		Removal of pork: Distributes pork calories no longer	CCP_S1 LAFA_S1



household (2.5 persons) level, or 2) as a specific single meal. The system boundaries encompass the production of raw materials (i.e., feed cultivation) and end with the purchase, preparation, consumption, and disposal of packaging and food waste in a typical U.S. household.

2010	Intake: Adults)		consumed to all other food groups based on the caloric distribution of those foods.	
Loss-Adjusted Food Availability Database (LAFA)	The USDA LAFA database is an accounting scheme as a proxy for food consumption based on disappearance data; it functions as an indirect estimation of food supply chain flows. It accounts for most of the food consumed in the U.S.		Increase in pork: Double pork calories consumed by decreasing calories from all other food groups based on the caloric distribution of those foods.	CCP_S2 **LAFA_S2**
Dettling et al. (2016) based on NHANES	The foods considered in this work were distributed to the food subgroups used in the previous dietary scenarios. A diet was created from the reported meals by adding breakfast, lunch, and dinner together.		Increase in pork: Double pork calories consumed by decreasing calories from only beef and poultry based on the caloric distribution of those foods.	CCP_S3 **LAFA_S3** **Meals (3) Scenarios**
USDA Dietary Guidelines 2010	Current specialty consumption diets (Usual US Intake: Adults)		Recommended Food Pattern (RCP) 2011	RCP
			Lacto ovo Vegetarian Food Pattern 2011	RCP_Veg LAFA_Veg

Effects represented in the foreground infrastructure were not included in the analysis; however, background infrastructure from processes such as electricity generation was included through the Ecoinvent database. Where data are incomplete, substitute unit operations were identified in Ecoinvent. In determining whether to include specific inputs, cut off criteria were established using a 1% cut off threshold of any input; however, if data were readily available, they were included. The allocation procedures followed the ISO 14044 hierarchy. To provide a robust methodological basis, we constructed both processes based and input-output (IO) hybrid models for each comparison.

The impact methodology used for GHGEs estimation was IPCC 2013 (Myhre *et al.*, 2013), which contains the global warming potentials with a timeframe of 100 years. IMPACT World+ midpoint and endpoint methods (IMPACT World+, 2017) were used for land occupation, water use impacts, and non-dietary human health impact, respectively. SimaPro 8.4 was used to create computational impact assessment models. Monte Carlo Simulation (MCS) was used to quantify and characterize the propagation of uncertainty ranges of input data to uncertainty in the final result.

3 Results

Figure ES-1 presents the potential GHGEs of six iso-caloric (2,000 kcal) dietary patterns computed with process-based and IO-based models. Both approaches give similar trends. Using the process-based analysis, current food consumption patterns (CCP) contribute 8.0 kg CO_2-eq/person/day. Red meat and dairy products, including losses, are major contributors to this

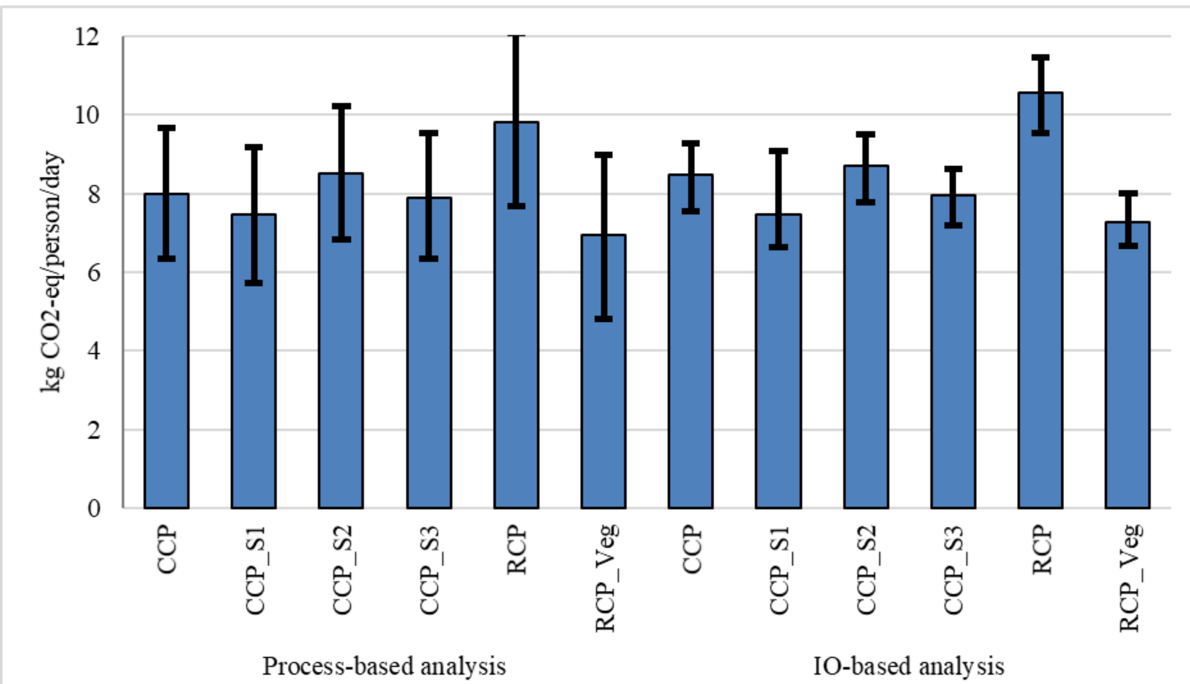


Figure ES-1. Comparative GHG emissions of multiple dietary scenarios based on USDA Dietary Guidelines and Food Patterns associated with process-based and IO-based analysis. The grey bars represent 95% confidence intervals, based on 1000 Monte Carlo simulations.

result. The process-based analysis also showed that the recommended consumption pattern (RCP) scenario has the largest GHGE, 9.8 kg CO_2-eq/person/day. In this scenario, emissions associated with milk/dairy, red meat, and fruit/juices groups contributed the most to the result. Somewhat surprisingly, GHGEs associated with food consumption and loss is not reduced by a shift to align with RCP dietary guidelines. In this study, retail and consumption stages contributed significantly to the higher emissions. The recommended reductions in consumption of red meat, poultry, grains, eggs, fats/oils, sweeteners, and associated food losses decrease GHGEs, however, the change is offset by significant increases in consumption and emissions from vegetables, fruit/juices, milk/dairy, fish/seafood, and beans/peas products. The CCP_S2 scenario, which doubled the daily consumption of pork to diet and subtracted an equal number of calories from the remaining food groups, increases GHGEs, as shown in Figure ES-1. The CCP_S3 scenario, which doubled daily consumption of pork in the diet and subtracted an equal number of added calories from beef and poultry, has the second lowest GHGEs at 7.9 kg CO_2-eq/person/day based on IO-based analysis, which is lower than the current food consumption patterns (CCP). This result indicates that doubling the daily consumption of pork by reducing beef and poultry consumption has the potential to reduce GHGEs. The USDA recommended vegetarian diet (RCP_Veg) has the lowest GHGEs at 6.9 kg CO_2-eq/person/day from the process-based analysis. The IO-based analysis had relatively narrow confidence intervals because there are fewer uncertain input values and parameters in the IO-based model compared to the process-based model.

Figure ES-1 compares the GHGEs of each meal scenario with and without pork for breakfast, lunch, and dinner. For this series of scenarios, the pork-free meals have had an isocaloric substitution of beef and poultry. The four major food groups contributing the most to GHGEs in pork-free meals are beef, fish/seafood, poultry, and vegetables. Pork-free meals displayed slightly higher GHGEs than pork-containing meals, but the difference is not particularly significant. The impact reduction of removing pork from the diet was offset by increased beef and poultry consumption.

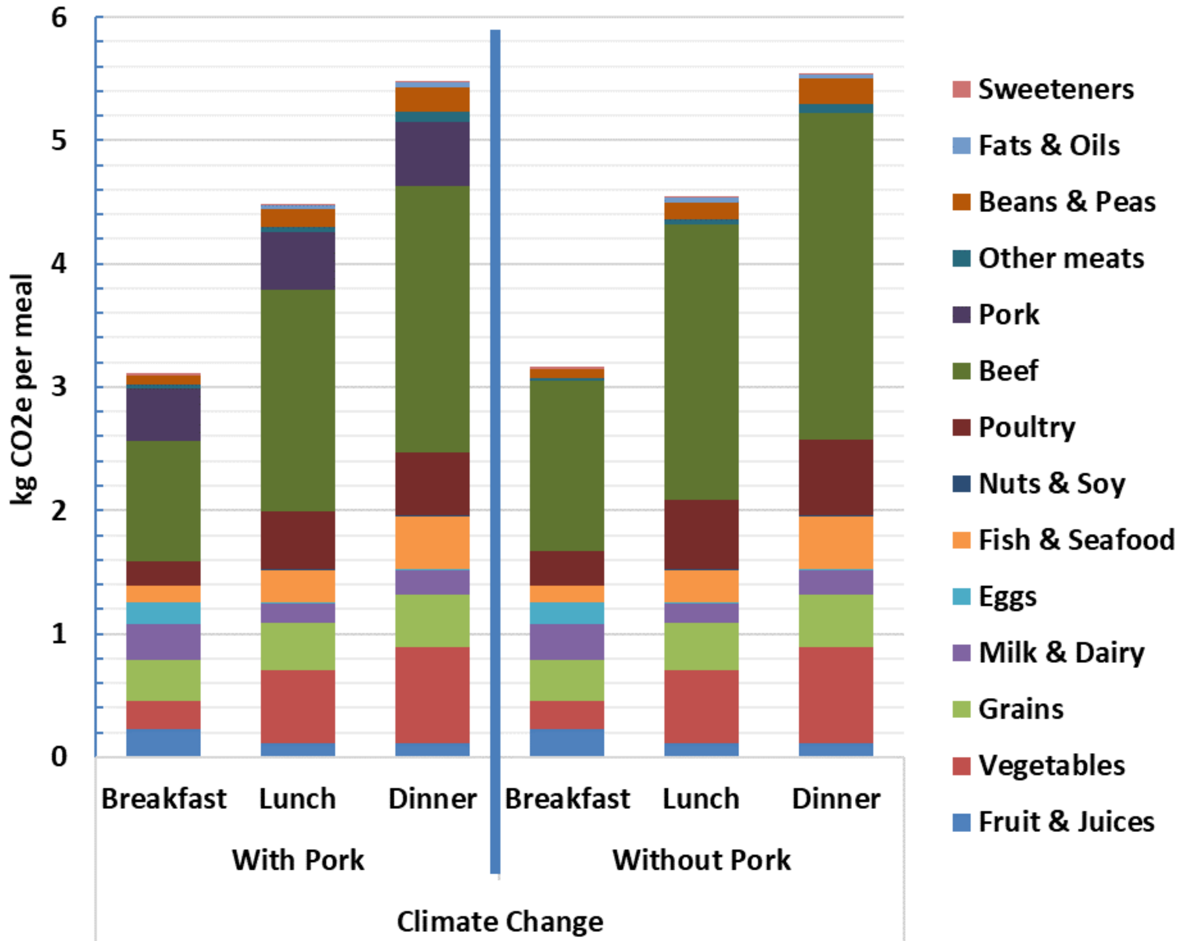


Figure ES-1. Greenhouse gas emissions associated with iso-caloric meals with pork and without pork.

Figure ES-2 presents the dietary human health impact of five scenarios relative to the baseline (CCP_2550) in the unit of µDALY[1] per person per day. A DALY (disability-adjusted life year) is a quantitative metric that accounts for the combined burden of disease including mortality and morbidity. This assessment is based on non-communicable disease risk factors for various food groups important in the global burden of disease database. We analyzed the impacts of dietary choices on human health using a risk assessment framework with four disease states (coronary heart disease (CHD), diabetes, stroke, and colorectal cancer). As shown in the CCP_S1 scenario,

[1] Approximately 30 seconds.

shifting to diets without pork would have health benefits; however, it should be noted that the global burden of disease data does not differentiate among red meats' health effects. Compared with the reference scenario (CCP_2550), we estimate that a pork-free diet (CCP_S1) would result in 7.4 μDALY averted per person per day. By adopting the USDA recommended diet (RCP), the health benefit increases to 16.9 μDALY averted per person per day. The health benefit further increases with recommended vegetarian diet.

Figure ES-3 shows simulation results from the pairwise comparison of meals as a percentage of 1,000 MCS runs. Meals with pork had lower GWP for 80% of the simulations compared to pork-free meals. Meals with pork had a lower land occupation impact than pork-free meals for 100% of the simulations. On the other hand, pork-free meals performed better than pork-containing meals in water use (55% directional, but not significant) and fossil fuel depletion (100% of the simulations). These results indicate that removing pork from the diets and substituting with beef and poultry is likely to have detrimental effects on global warming and land occupation impacts. In contrast, removing pork from the diets is also likely to slightly decrease the impacts of water use and increase fossil fuel depletion. In conclusion, dietary or meal choices lead to unavoidable impact trade-offs. This fact implies that simple one-size-fits-all solutions do not exist. Nonetheless, there are opportunities for improvement of environment and human health effects of diet and meal choices.

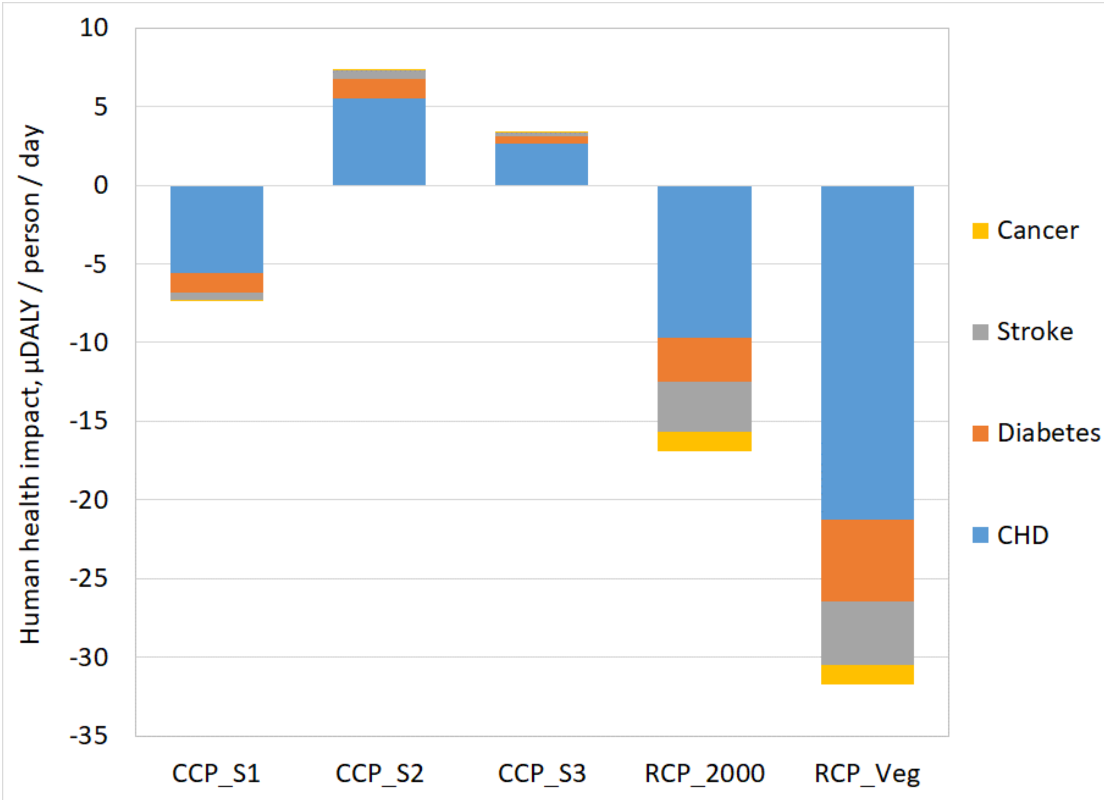


Figure ES-2. Dietary related human health impact of five distinct dietary scenarios relative to the baseline scenario (CCP) reported in µDALY per person per day.

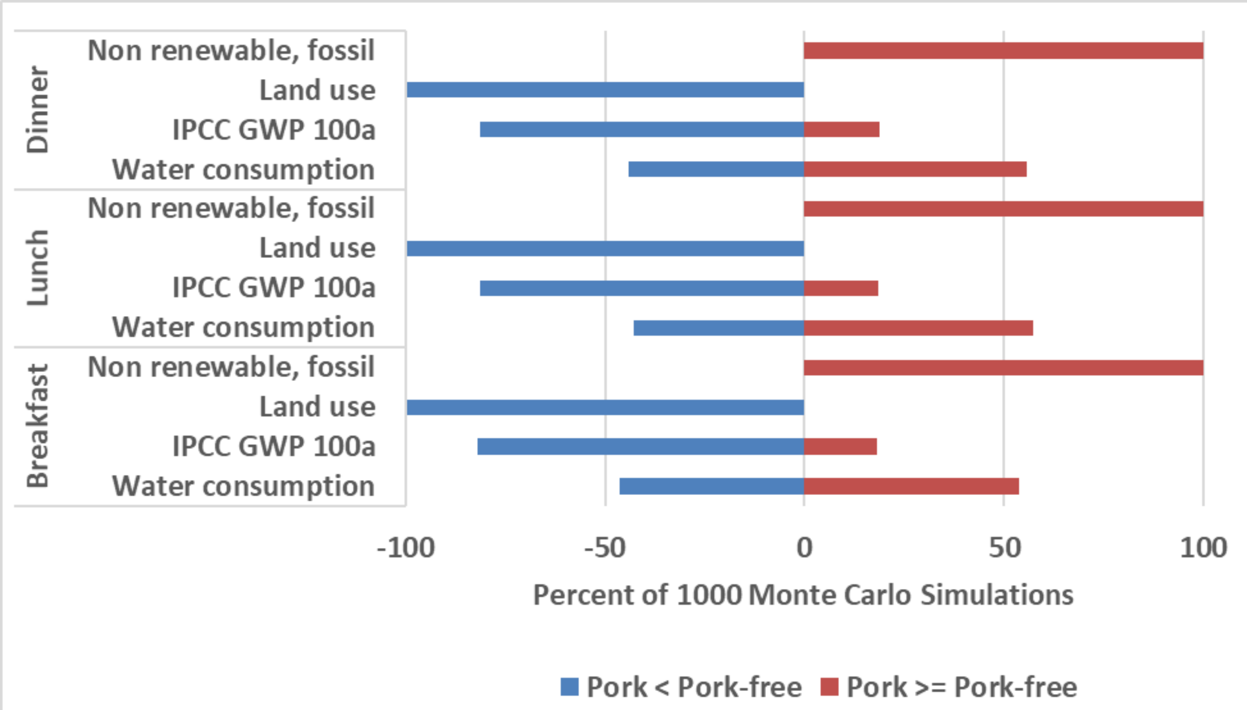


Figure ES-3. Pairwise Monte Carlo comparison of pork meals versus pork-free meals. This figure can be interpreted as providing the relative certainty of the direction of the difference in impact between scenarios. Thus, breakfasts with pork have an approximately 75% probability of lower carbon footprint.

A Comparative Life Cycle Assessment of Calorically Equivalent Meals with and without Pork

1 Introduction and Background

Increasing awareness of environmental and health issues related to food production, distribution, and consumption has led to studies focused on understanding the connection between nutritionally sound consumption and potential environmental impacts. Life cycle assessment (LCA) has been used to analyze the entire life cycle of single, specific foods from production to consumption to determine the potential environmental impacts. Many LCAs fail to address nutritional aspects of the food (Ernstoff *et al.*, 2014) and those that do incorporate nutrition tend to focus on one environmental impact, e.g., carbon emissions, instead of multiple impacts such as energy, water, and land use. For instance, Heller and Keoleian (2015a) studied a shift from the average American diet to following the USDA recommended dietary guidelines. The study used a meta-analysis of LCA data to construct values of greenhouse gas emissions (GHGEs) for individual foods. The results from this study concluded that by shifting from the current average American diet to the recommended USDA dietary guidelines; there would be a small increase in GHGEs. Other studies have concluded that meals containing meat have higher environmental impact than meals without meat. Dettling et al. (2016) studied whether switching to plant-based meals from meals containing meat decreased environmental impacts. The study reported that by shifting from a meal containing meat to a meatless meal, GHGEs would decrease by approximately 40%. The study covered multiple environmental impact categories, but the meat and meatless meals were compared on a mass basis, thereby ignoring differences in nutritional characteristics. A majority of studies evaluating the reduction of meat consumption conclude that potential environmental impacts will decrease (Baroni *et al.*, 2007; Aston, Smith and Powles, 2012; Scarborough *et al.*, 2014; Chen *et al.*, 2016; Goldstein *et al.*, 2016). However, not all studies reach that conclusion. For example, Tom et al. (2016) found that shifting from meat products like pork and chicken to a diet with high amounts of fruits, vegetables, and seafood increases impacts for most of the environmental impact categories. This was because fruits, vegetables, and seafood use significant natural resources and have higher emissions per calorie intake.

The work reported in this document is a field-to-fork LCA of carbon, water, and land footprints of diets/meals with pork versus nutritionally equivalent (iso-caloric) diets/meals without pork, including an assessment of health impacts. The data used in this study are primarily from USDA Dietary Guidelines and Food Patterns (Office of Disease Prevention and Health Promotion, 2015), the Loss-Adjusted Food Availability (LAFA) database (USDA, 2015b), and the National Health and Nutrition Examination Survey (USDA, 2018) as well as scientific literature and academic reports. Our analysis utilizes the SimaPro© software platform to perform the impact assessment. Except for some specific scenarios, all diets or meals studied are calorically equivalent (2,000 kcal), which provides a representative basis for evaluating the environmental impacts associated with food choices.

1.1 Literature Review

The focus of this study is to analyze several different diet and meal plan scenarios with and without pork and to evaluate the respective environmental and health impacts. Several research articles have previously reported on these topics. One study considered water footprint, GHGEs, and energy consumption for three dietary scenarios based on current food consumption patterns and USDA recommended Food Patterns (Tom et al., 2016). The dietary scenarios were compared according to the calories consumed per person. The results of this study show that decreasing caloric intake will decrease impacts in all three environmental categories evaluated; however, by following the USDA recommended dietary guidelines, impacts in the three environmental categories will increase. The reason for this is that the USDA's dietary recommendations for increased consumption of fruits, vegetables, dairy products, and fish/seafood offset reductions from decreased consumption of other foods. Following the recommended USDA dietary guidelines while reducing caloric intake will also increase environmental impacts. This study suggests that simply shifting diets away from red meat consumption will not necessarily decrease the environmental impacts due to complex interactions and supply chain differences (Tom et al., 2016).

Hallstrom et al. (2015) provide an evaluation of the scientific basis of dietary scenario analysis. They identify potential environmental effects of dietary changes and important methodological aspects by suggesting that functional units representing nutritional content instead of simply quantity consumed provides a more appropriate comparison between the food groups. Vieux et al.

(2012) also described the importance of choosing a functional unit that accounts for nutritional content. The most common method reported in the literature was to use iso-caloric dietary plans, so the diets will all have equal energy content. Many studies provided additional specifications to ensure that the diets/meals comply with recommended health and nutritional guidelines. One such specification is to use meal plans based on reported consumption data, such as NHANES, which are considered to be a realistic representation of food intake (Hallström *et al.*, 2015). However, it is important to note that people tend to change or falsely report their food consumption habits when self-reporting (Archer, Pavela and Lavie, 2015).

Ernstoff et al. (2014) proposed a system to compare the environmental impacts and health effects of dairy consumption. It used the global burden of disease (GBD) information and Disability Adjusted Life Years (DALYs) to differentiate and quantify health and environmental impacts. DALY is a way of measuring the burden of disease through a number of years lost due to premature death and poor health (Murray *et al.*, 2012). Ernstoff et al. (2014) also present a way to establish health responses to dietary change. Their study found that by increasing dairy consumption by one glass of low-fat milk per day, the consumer would benefit nutritionally. This article provides a basic analysis of health effects in an LCA framework and concludes that full production and consumption life cycle should be considered when evaluating the sustainability of diets. It also offers a basis for evaluating environmental and nutritional impacts to human health and stresses the importance of understanding both as they may contradict each other, as suggested by Norja et al. (2009). Stylianou et al. (2016) further developed these concepts into a combined nutritional and environmental LCA framework using milk as a case study.

Other studies focused on health and environmental benefits or consequences of red and processed meat. One such study was Aston et al. (2012); they concluded that by reducing intake of red and processed meat, there would be both health and environmental benefits. However, this study does not substitute other food groups for meat consumption to determine substitution effects on environmental and health impacts.

Although it is ideal to conduct a field-to-fork LCA, many activities are often excluded because they are assumed to have a small effect on the overall environmental impact. Many LCA studies of food include activities only up to the farm gate because agricultural production generally has the largest environmental impact (Schau and Fet, 2008; Sonesson, Davis and Ziegler, 2010).

Nonetheless, for foods that have small GHGEs during production, ignoring activities after the farm gate may significantly affect conclusions (Norja, Kurppa, and Helenius, 2009; Fazeni and Steinmüller, 2011; Van Dooren *et al.*, 2014; Hallström *et al.*, 2015). Some articles are very limited in their coverage of food groups as well as the number of assessed environmental impacts. Saxe et al. (2013) analyzed the environmental impacts of 31 food categories from farm to retail. In the study, three diets were analyzed: the average Danish diet, the recommended Danish diet, and the New Nordic Diet. The research concluded that reducing alcoholic drinks, hot drinks, and sweets by 50% would reduce GHGEs by the same amount as reducing red meat intake by 30%.

Ensuring a complete accounting of food waste is another important consideration in defining system boundaries. This data is usually found from the difference of per capita supply data and consumption data (Berners-Lee *et al.*, 2012). Venkat (2011) calculated the GHGEs associated with avoidable food waste throughout the life cycles of 134 food commodities and found that of the 16 food groups evaluated, beef was the largest contributor to GHGEs. It was also reported that emissions caused by wasted food associated with the production and processing phases were the highest of all the supply chain stages (that is the production of food that is ultimately wasted is the dominant source). Further down the supply chain, Heller & Keoleian (2015) used the LAFA data series to evaluate GHGEs associated with the production of edible food that is lost during the retail and consumer phases. This study also evaluated the GHGEs that arise from a shift from an average American diet to the USDA dietary guidelines. Heller & Keoleian (2015) concluded that an iso-caloric shift from the current U.S. average diet to USDA recommendations has the potential to increase diet-related GHG emissions.

The potential to reduce GHGEs is predominantly affected by the type of meat, specifically red meat and ruminant meat and produced and consumed animal products. Replacing ruminant meat in all diets with poultry and pork can decrease GHGEs by up to 35% (Hallström *et al.*, 2015). Another study by Dettling et al. (2016) used LCA to determine if switching to plant-based foods and away from meat consumption would decrease environmental impacts. They concluded that raising animals as food for humans has a greater environmental impact than consuming plant-based meals; however, nutrient content and equivalency were not accounted for in this study.

The potential for reduction of land use seems to rely largely on decreasing consumption of ruminant animals. A study by Audsley et al. (2010) shows that by substituting 75% of ruminant meat with poultry and pork, land use demand can be reduced by 40%. It has been calculated that global average per capita demand for land by 2050 will be 5,000 m^2, and by altering normal consumption to a diet with a reduced intake of ruminant and red meat, global average per capita land demand by 2050 would be 2,200-3,500 m^2 (Wirsenius, Azar and Berndes, 2010; Powell and Lenton, 2012). Stehfest et al. (2009) also studied the potential effects of alternate diets on climate change. They report that reducing or eliminating meat consumption leads to a significant reduction in land use with modest changes in cropland, but a dramatic reduction in grassland used. Some of this unused land could be used for reforestation and natural habitation. Consequently, Stehfest et al. (2009) found that transitioning to a low meat diet compared to a case of increased consumption (business as usual scenario up to 2050) could decrease GHGEs by 50% by 2050.

Weber and Matthews (2008) compared a life cycle assessment of GHGEs of food commodities to the distance the products travel to be distributed (food-miles). The study reports a complete LCA of GHGEs resulting from food products in the production, transportation and distribution phases. The analysis included upstream impacts of food and non-alcoholic beverages. The study found that if the average American household bought locally grown food, they would decrease GHGE a maximum of 4-5%.

In future research studies, it is suggested that additional sustainability factors such as loss of biodiversity, acidification, etc. need to be assessed. Some authors assert that these factors can be correlated to GHGEs and land demand for agriculture (Rockström *et al.*, 2009; Hallström, Röös and Börjesson, 2014; Van Dooren *et al.*, 2014), although the correlation may strongly depend on location. As reported by Audsley et al. (2010) and several other studies, replacing ruminant red meat with chicken and pork leads to a reduction of environmental impacts. As suggested by numerous authors, it is important to consider both nutritional and environmental impacts as each of these factors together are significant sustainability issues. Nutritional equivalency is also an important factor in determining realistic and healthy dietary and meal scenarios. By performing an LCA on nutritionally equivalent diets/meals, the results will more realistically evaluate the full complement of environmental effects of changes in consumption patterns (Ernstoff *et al.*, 2014; Kendall and Brodt, 2014; Auestad and Fulgoni, 2015; Drewnowski *et al.*, 2015; Stylianou *et al.*, 2016).

2 LCA Methods

The following section presents the goal and scope of the study, data sources, dietary scenario methodology, sample meal plan, lifecycle inventories, life cycle impact assessment, and uncertainty analyses. The two main components analyzed in this study are dietary scenarios and meal plans.

2.1 Goal and Scope Definition

The goal of the study is to compare diets and meals with and without pork. A series of scenarios, described below, were constructed based on different data sources for consumption patterns, including the Loss-Adjusted Food Availability (LAFA) database (USDA ERS, 2017) and the National Health and Nutrition Examination Survey (NHANES) (USDA, 2018). The scope of the study is from cradle-to-grave (or farm-to-fork), inclusive of all extractions from nature through the final disposal of packaging and food waste, with a full accounting of food loss/waste across all production and consumption stages.

2.1.1 System Boundaries and Cut-off Criteria

The system boundaries encompass the production of the raw materials and include the purchase, preparation, consumption of food, and disposal of food waste. Non-dietary and dietary health impacts associated with diets/meals are considered. Environmental impacts from infrastructure are not considered for foreground processes. The cut-off threshold for inventory inputs in the system was 1%. Any processes that contributed to the environmental impact that is estimated to be less than 1% were eligible for exclusion; nonetheless, if data could be readily obtained for an input or process, it was included. Figure 2.1 depicts the lifecycle stages of food products considered in this study.

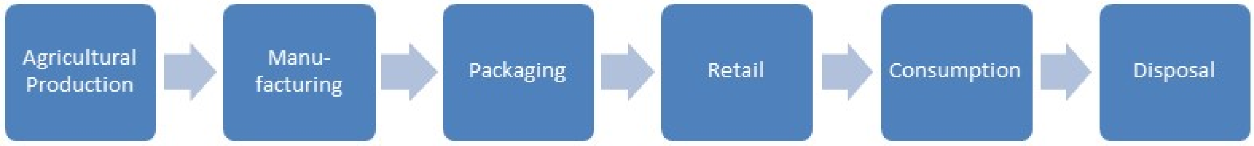


Figure 2.1. Lifecycle stages in the food supply chain system.

2.1.2 Functional Units

In this study, there were two functional units. The first functional unit was defined as the kilocalories consumed in a day by the average U.S. adult. The product systems assessed by this functional unit are referred to as dietary scenarios. The second functional unit was defined as the kilocalories in a specific meal (breakfast, lunch or dinner) consumed by the average U.S. adult. The product systems assessed by this functional unit are referred to as meal plans.

Nutritional equivalence and diet/meal components were primarily derived from USDA Dietary Guidelines and Food Patterns, LAFA database, and NHANES data. Eleven dietary scenarios, as well as six sample meal plans, were analyzed. The dietary scenarios included two baseline diets: USDA Dietary Guidelines/Food Patterns and consumption according to the LAFA database. These baseline diets were used to formulate eight alternative iso-caloric dietary scenarios. Two other dietary scenarios were adapted from USDA recommended food patterns with and without meat (United States Department of Agriculture, 2011). Six meal plans were constructed similarly, creating two sets of meal plans: pork and pork-free meals. The dietary scenarios and meal plans are described in detail in the following sections.

2.1.2.1 Dietary Scenarios

The dietary scenarios analyzed in this study were put into two separate groups according to the calorie content of the diets. The first group of dietary scenarios was based on a 2,000 kcal/day diet (Table 2.1). A baseline diet following the current consumption pattern (CCP) was established using the "Usual U.S. Intake: Adults" consumption as reported in the USDA Dietary Guidelines 2010. This diet was adjusted to create three iso-caloric alternative diets, each with varying amounts of pork. In each alternative scenario, the amount of each specific food group was determined according to its respective caloric contribution in the baseline diet. Scenario one (CCP_S1) was formulated by removing pork entirely from the baseline diet and increasing the remaining food groups proportionately, such that the total caloric content remained at 2,000 kcal/day. Scenarios two and three were formulated by doubling the amount of pork in the baseline diet while decreasing other food groups. In scenario two (CCP_S2), all food groups were decreased proportionately, whereas, in scenario three (CCP_S3), only beef and poultry were reduced. In addition to these four consumption-based dietary scenarios, two more diets based on USDA recommendations were included. These diets were modeled after the standard adult diet as defined by USDA Recommended Food Patterns (RCP) and the Lacto-Ovo Vegetarian Adaptation

Table 2.1. Energy content delivered by each food group in the dietary scenarios based on current consumption patterns and USDA recommendations. Values are presented in kilocalories.

Food Groups	CCP	CCP_S1	CCP_S2	CCP_S3	RCP	RCP_Veg
Fruits	98.53	102.23	94.84	98.53	197.01	197.01
Vegetables	115.21	119.53	110.90	115.21	176.65	176.65
Grains	499.63	518.35	480.91	499.63	468.41	468.41
Dairy	229.45	238.05	220.85	229.45	458.90	458.90
Eggs	28.80	29.88	27.72	28.80	28.80	41.18
Fish/seafood	16.90	17.53	16.26	16.90	40.46	-
Nuts/seeds	43.52	45.15	41.89	43.52	52.11	310.18
Poultry	77.86	80.78	74.94	43.04	97.33	-
Beef	126.35	131.09	121.62	83.65	91.20	-
Pork	77.52	-	155.04	155.04	55.76	-
Other Meats	1.75	1.81	1.68	1.75	1.26	-
Legumes	9.93	10.30	9.56	9.93	19.86	19.86
Oils	158.83	164.78	152.88	158.83	238.25	167.66
Solid Fats	361.20	374.73	347.67	361.20	134.40	134.40
Sugars	300.99	312.27	289.71	300.99	121.92	121.92
Total	*2,146.48*	*2,146.48*	*2,146.48*	*2,146.48*	*2,182.31*	*2,096.17*

(RCP_Veg).

The second group of dietary scenarios was formulated using the loss-adjusted food availability (LAFA) database from the most recent year available, 2014 (Table 2.2). This database provides information on the consumption of food in the U.S., adjusted for loss (USDA ERS, 2017). The baseline diet was again based on current food consumption patterns, approximately 2,550 kcal, while the other three diets were adjusted to create three calorically equivalent alternative diets following the same approach as the first group of dietary scenarios. A LAFA-based vegetarian diet was also constructed (LAFA_Veg) using the same food components as the USDA recommended vegetarian diet (no fish/seafood and no meat). For this diet, the amount of each food group was adjusted to provide the same total calories as the baseline diet (2,550 kcal) by proportionately increasing the calories from each remaining food group.

2.1.2.2 Meal Plans

In addition to the dietary scenarios, six meal plans were constructed using NHANES data from 2011-2012 (Dettling *et al.*, 2016). NHANES is a program that assesses the health and nutrition of children and adults in the U.S. through physical examinations and surveys. Surveys ask participants to self-report what they ate throughout the day for each meal including snacks. Since this data is self-reported, it may include more or less food than was actually consumed (Archer, Pavela and Lavie, 2015). In 2011-2012, approximately 5,000 adult males and females completed the survey providing a detailed accounting of the foods consumed within a 24-hour period (USDA, 2018). The data were not indicative of specific individuals but of a sample of the American population. For the purposes of this study, snacks were not included. Some foods in the NHANES meal plans were more specific than the general food groups defined in this study. We assigned these food items to the nearest corresponding food group and assigned equivalent calories from the LAFA database. Table 2.3 presents the caloric content by food group for the individual meals in the comparison. Once the specific foods were assigned to their corresponding groups, the weight consumed in grams was converted to calories.

Table 2.2. Energy content delivered by each food group in the dietary scenarios based on the LAFA database. Values are presented in kilocalories.

Food Groups	LAFA_Current	LAFA_S1	LAFA_S2	LAFA_S3	LAFA_Veg
Fruits	72.07	74.90	69.24	72.07	86.31
Vegetables	119.72	124.42	115.02	119.72	143.38
Grains	553.76	575.49	532.03	553.76	663.21
Dairy	231.77	240.86	222.67	231.77	277.58
Eggs	33.84	35.17	32.51	33.84	40.53
Fish/seafood	13.09	13.60	12.58	13.09	-
Nuts/seeds	74.79	77.72	71.85	74.79	89.57
Poultry	156.18	162.31	150.05	102.52	-
Beef	156.95	163.11	150.79	113.23	-
Pork	97.38	-	194.75	194.75	-
Other Meats	1.96	2.04	1.89	1.96	-
Legumes	9.11	9.47	8.75	9.11	10.91
Oils	243.92	253.49	234.34	243.92	292.12
Solid Fats	417.96	434.37	401.56	417.96	500.57
Added Sugars	396.24	411.79	380.69	396.24	474.55
Total	*2,578.74*	*2,578.74*	*2,578.74*	*2,578.74*	*2,578.74*

The NHANES data regarding the composition of individual meals typically consumed were adapted from Dettling et al. (2016); however, in that study, the "meals containing meat" and "meatless meals" were not iso-caloric, but matched based on weight. For this assessment, the meals containing pork were adjusted to have the same energy content as their pork-free counterparts. We believe this provides a more appropriate basis for comparing American eating patterns for meals with and without pork. The standard meals were based on the average food consumption reported as pork-containing breakfast, lunch, and dinner. Three alternative meals were created without pork: pork-free breakfast, lunch and dinner. These alternative meals were constructed by removing pork from the meals and substituting an equal number of calories with beef and poultry only. Meals with and without pork were designed to have the same number of kilocalories.

Table 2.3. Energy content delivered by each food group in the meals with and without pork. Values are presented in kilocalories.

Food Groups	Meals with pork			Meals without pork		
	Breakfast	**Lunch**	**Dinner**	**Breakfast**	**Lunch**	**Dinner**
Fruits	30.08	15.42	15.42	30.08	15.42	15.42
Vegetables	28.45	75.02	97.55	28.45	75.02	97.55
Grains	337.16	374.97	428.49	337.16	374.97	428.49
Dairy	54.17	28.75	35.66	54.17	28.75	35.66
Eggs	62.76	3.57	3.77	62.76	3.57	3.77
Fish/seafood	9.38	18.81	30.79	9.38	18.81	30.79
Nuts/seeds	2.27	6.07	4.47	2.27	6.07	4.47
Poultry	40.33	98.80	107.28	59.09	119.62	130.15
Beef	58.16	106.19	128.04	81.19	131.73	156.10
Pork	41.79	46.36	50.93	-	-	-
Other Meats	1.58	2.53	4.94	1.58	2.53	4.94
Legumes	5.83	11.55	16.76	5.83	11.55	16.76
Oils	9.71	40.68	42.53	9.71	40.68	42.53
Solid Fats	-	-	-	-	-	-
Added Sugars	-	-	-	-	-	-
Total	*681.67*	*828.70*	*966.64*	*681.67*	*828.70*	*966.64*

2.1.3 Intended Audience

This report is primarily intended for internal use by the National Pork Board (NPB). The NPB may choose to share the report with stakeholders from the pork industry including growers, processors, packaging companies, and retail. Full compliance with ISO standards requires a third-party review, by at least one expert, prior to distributing the report to external stakeholders.

2.1.4 Allocation

Where allocation of inputs was required, the allocation procedures follow the ISO 14044 hierarchy.

2.2 Life Cycle Impact Assessment

The life cycle impact assessment (LCIA) was conducted using SimaPro 8.4 and considered the environmental impact categories of global warming potential (GWP), water use, and land use. We adopted the IPCC 2013 100a method (Myhre *et al.*, 2013) for GWP, the IMPACT World+ method for land occupation (IMPACT World+, 2017), and the AWARE method for water use impacts (Boulay *et al.*, 2018).

2.2.1 Human Health Impacts of Dietary Choices

Diet is closely linked to non-communicable health problems including heart disease, obesity, diabetes, cancer, etc. Each year these health issues affect an increasing number of people in U.S., and globally. Therefore, we analyzed the impacts of dietary choices on human health by using a risk assessment framework with five distinct dietary scenarios relative to a baseline scenario. The four disease states compared to the baseline scenario were coronary heart disease (CHD), diabetes, stroke, and colorectal cancer. They were chosen because they were the highest causes of DALYs (disability-adjusted life year). For each scenario, the measurement unit was µDALY (disability-adjusted life year) per person per day. The Global Burden of Disease (GBD) study quantifies global levels and trends of health loss from hundreds of diseases, injuries, and risk factors, specifically including the disease burden from diet (IHME, 2013). We adopted the 2015 US-specific GBD reports detailing the risk of mortality and morbidity associated with dietary choice. The GBD estimation of DALYs is based on CCP 2,550 kcal, and therefore, unlike environmental impact assessment in this report, human health assessment is based on dietary patterns of 2,550 kcal (baseline = CCP_2550). The GBD study included 14 different components including a diet low in fruits, vegetables, grains, nuts/seeds, and milk and a diet high in red meat, processed meat, sugar-sweetened beverages, etc. In this study some of the scenarios involve changes to multiple components of the diet or meal (_S1) for which we evaluated changes in the intake of vegetables, fruits, milk/dairy, grains, and red meat. A full listing of the 2015 DALYs of dietary risks for all ages and both sexes in U.S. is included in the appendix.

Table 2.4 presents the relative risk factors based on current dietary patterns and references adopted in this study for the selected human diseases. We chose these references by reviewing meta-analyses and existing cohort studies. In each case, a dose-response relationship was

Table 2.4. Relative dietary risk factors adopted in this study.

Food Group	**Relative risk factor**				**Note**	**Reference**
	CHD	**Diabetes**	**Stroke**	**Colon Cancer**		
Vegetables	0.96	0.93	0.97	0.93	106 g per day increment	Springmann et al., 2016
Fruits	0.93	0.94	0.89	0.93	106 g per day increment	Springmann et al., 2016
Milk/Dairy	-	-	0.85	0.93	200 g per day increment	Stylianou et al., 2016
Grains	0.79	0.79	0.79	-	65 g per day increment	Mellen et al., 2008
Red meat	1.25	1.15	1.1	1.01	100 g per day increment	Springmann et al., 2016

obvious, and a consistent result was apparent. It is evident from Table 2.4 that increasing consumption of vegetables, fruits, milk/dairy, and grains is beneficial for health (risk factor less than 1), but the additional intake of red meat leads to the detrimental health outcome (risk factor greater than 1).

2.3 Life Cycle Inventory

We developed life cycle inventory (LCI) models based on two distinct LCA frameworks: process-based LCA and input-output-based lifecycle assessment or IO-LCA. This comparative methodological analysis provides strong support for the robustness of the key findings. For the process-based analysis, each food item or food group in each scenario was represented by specific LCI data available in existing databases (Ecoinvent 3.3, Ecoinvent Centre, 2016) as part of the raw material production stage. Where LCI data was missing, a similar surrogate food item was chosen to substitute. Using a tiered input-output (IO)-based analysis, we analyzed the potential environmental impacts of individual food items by mapping food consumption and losses to commodity sectors that were included in the input-output tables representing the whole U.S. economy, or to disaggregated sectors. The following sections detail the LCI calculations for each stage of the food life cycle for the process-based LCA model.

2.3.1 Process-based LCI Methodology

The life cycle inventory (LCI) data for the agricultural production stage included cultivation of the plant or husbandry for animal products. Reference flows for this stage and the other life cycle stages of food production were determined by the number of calories consumed for each food product, adjusted for food loss/waste in the post-production supply chain. The inventory flows in the processing and retail stages come primarily from facility energy use (machinery, refrigeration, etc.) and water use. LCI data for packaging and transportation were not calculated on an individual food basis but were based on the overall quantity of food products consumed. Inventory flows associated with packaging for food products were primarily related to the energy, land, and water needed to acquire, manufacture and distribute packaging materials. The transportation stage included all transport modes necessary to deliver the food products to their retail destinations. Inventory flows in the consumption stage accounted for the energy and water used for storing, cooking, and consuming food.

2.3.1.1 Food Groups

Food groups were constructed based on USDA Food Patterns in accordance with the LAFA database. Further disaggregation of food groups was made based on the primary goal of this report, which is to present environmental and health impacts of diets and meals with varying amounts of pork consumed. The main food groups are presented in Table 2.5 along with their subcategories.

2.3.1.1.1 Fruits and Juices

For the main food group of "fruits and juices," data from "total fruit-fresh and processed" was used for daily per capita gram and calorie consumption. The two subcategories of "fruits and juices" are "whole fruit" and "fruit juice." Data for "whole fruit" was estimated from foods considered whole fruit in several subcategories from the LAFA "fruit" spreadsheet. The value of fruit consumed in grams per day was reported as "per capita availability adjusted for loss-g/day"

Table 2.5. List of dietary food groups from USDA Food Patterns and LAFA database.

Food group	Subcategory
Fruits and Juices	Whole fruit Fruit juice
Vegetables	Dark green vegetables Starchy vegetables Red and orange vegetables Other vegetables
Grains	Whole grains Refined grains
Milk and milk products (Dairy products)	Milk Dry milk Ice cream Yogurt Cheese Soymilk
Protein foods	Eggs Fish/seafood Nuts, seeds, and soy products Poultry Beef Pork Other meats Legumes (beans and peas)
Oils Solid fats Added sugars	

for the year 2014. “Fruit juice” data was calculated from the ratio of consumed fruit juice as depicted in the “fruit” section of the LAFA data. The LAFA database also reports the caloric energy content of foods (kcal/g).

2.3.1.1.2 Vegetables

Data for daily per capita consumption of the main food group “vegetables” was taken from the “total vegetables-fresh and processed” category from the LAFA database. There are four subgroups under this main food group, which included dark green vegetables, starchy vegetables, red and orange vegetables, and other vegetables. To calculate the daily per capita consumption for each subcategory, the consumption under “per capita availability adjusted for loss-g/day” was used to create the ratio of each specific subcategory consumed. Gram to calorie conversions for each sub category were taken from Appendix E-3.1: Adequacy of USDA Food Patterns (USDA, 2015a). This appendix presents calories per cup for each of the vegetable subgroups. We note that the caloric content of vegetables is relatively uniform.

2.3.1.1.3 Grains

Daily per capita consumption for the main food group “grains” was taken from the LAFA grain spreadsheet. The daily consumption in grams was taken from the “total grains” category consisting of whole grains and refined grains. The daily consumption of the “whole grains” subcategory was calculated by dividing the consumption of whole grains by the daily “total grains” grams of consumption. Calorie conversions for whole grains were estimated by averaging the calories/day from the following sub-categories of the “grains” section from the LAFA database: “whole grains,” “wheat flour,” “rye flour,” “oat products,” and “barley products.” Calorie per day conversions for the “refined grain” category was estimated by averaging calories/day of the following groups under “grains” in the LAFA database: “corn products,” “corn flour and meal,” “corn hominy and grits,” “corn starch,” and “rice.”

2.3.1.1.4 Dairy Products

The “dairy products” category was constructed from the “total dairy products” category in the LAFA database. The daily per capita consumption of “total dairy products” was distributed to the dairy product subcategories based on the ratio for each of the dairy subgroups. Calorie conversions were available for each subgroup in the LAFA dairy database.

2.3.1.1.5 Protein Foods

The "protein foods" category was mainly taken from the LAFA dataset titled "*meat, poultry, fish, eggs, and nuts.*" All subcategories for the protein foods were accounted for in this dataset except for legumes. Information for legumes was obtained from the LAFA "vegetables" dataset. We disaggregated the "protein foods" category into eggs, fish/seafood, nuts/seed/soy, poultry, beans/peas (legumes), and red meat. In addition, "red meat" was disaggregated into "beef," "pork," and "other meats." "Other meats" consisted of lamb, veal, and game meat. Values for the daily per capita consumption for each subcategory were available in the LAFA database. Grams to calorie conversions were obtained from the LAFA database.

2.3.1.2 Food Manufacturing

Food manufacturing plants process raw agricultural livestock and products to intermediate or final products for consumption. The food manufacturing industry is the fifth largest energy consumer in the U.S. manufacturing sector (US Census Bureau, 2016). There are more than 30,000 food processing plants in U.S. and the number of plants has been increasing according to the data available from the Census Bureau. Since the circumstances of food manufacturing and processing are very broad, we adopted "2015 Annual Survey of Manufacturers" data to estimate electricity and fuel usage (US Census Bureau, 2016). Data in this survey present the cost of purchased electricity and fuels consumed for all North American Industry Classification System (NAICS) level industry sectors. We used 2015 average industrial energy prices in the U.S. to convert expenditures for electricity and fuels to units of energy ($0.0943 per kWh, $2.59 per MMBtu). According to the data available, the food industry consumes about 7% of the total electricity used by the manufacturing sectors. In addition to electricity, fossil fuels are used, with natural gas being the dominant source. Thus, we assumed that natural gas consumption was representative of all fuels consumed. Table 2.6 presents energy usage in the food manufacturing stage based on the cost of electricity and fuels purchased for NAICS food industry sectors. The meat processing industry followed by grain milling, dairy manufacturing, fruits/vegetables preserving spent the most money on electricity and fuels. Most NAICS industry codes aligned well with the food group we constructed, however there were a few exceptions, but these substitutions are unlikely to affect the overall results, energy usage in these substituted manufacturing stages needs further study.

Water consumption in food manufacturing plants was also accounted. The food industry uses a large volume of water for various purposes. Water is used to clean floors, sanitize processing equipment and vessels, and to rinse raw food products before processing. Water is also required

Table 2.6. Electricity and fuel usage in food manufacturing stage based on the cost of electricity and fuel purchases reported for NAICS food industry sectors during 2015.

NAICS Code	Food industry	Electricity purchased (million $)	Fuel purchased (million $)	Manu-factoring (billion kg)	Electricity use (kWh/kg)	Fuel usage (MMBtu /kg)
3112	Grain and oilseed milling	844.0	765.0	42.40	0.21	6.97E-03
31121	Grain milling	316.0	131.0	27.10	0.12	1.86E-03
31122	Fats/Oils manufacturing	353.0	362.0	13.80	0.27	1.01E-02
311224	Nuts/Seeds processing	175.0	272.0	1.51	1.23	6.96E-02
3113	Sugar manufacturing	286.0	358.0	19.70	0.15	7.02E-03
3114	Fruit and vegetable preserving	708.0	546.0	65.30	0.12	3.23E-03
31141	Vegetables preserving	428.0	330.0	36.90	0.12	3.45E-03
31142	Fruits/Juices preserving	280.0	216.0	28.40	0.10	2.94E-03
3115	Dairy product manufacturing	775.0	456.0	35.60	0.23	4.95E-03
3116	Animal processing	1387.0	683.0	24.70	0.60	1.07E-02
31161	Red meat processing	816.0	455.0	14.70	0.59	1.19E-02
311615	Poultry processing	571.0	228.0	9.93	0.61	8.88E-03
3117	Seafood preparation	89.5	143.0	2.21	0.43	2.50E-02
31191	Snack food manufacturing	170.0	132.0	4.45	0.41	1.15E-02
31192	Coffee and tea manufacturing	52.9	36.7	0.95	0.59	1.49E-02

for cooling water, steam, and refrigeration systems (Kirby, Bartram and Carr, 2003). Water use data exists for some food processing including vegetables, fruits/juices, milk/dairy, grains, red meat, poultry, and fats/oils (NWFPA, 2017). According to Maupin et al. (2014), total industrial water usage was an estimation of 15,900 million gallons per day in 2010. We assumed that 7% of the total industrial water usage accounted for the food industry sector which is the same as the

Table 2.7. Water use in the food processing industry.

Food Group	**Water use (l/kg)**
Grains	7.87
Beef	6.21
Pork	6.21
Other Meat	6.21
Poultry	14.10
Eggs	7.87
Fats and Oils	0.46
Vegetables	22.70
Fruits and Juices	85.60
Dairy	2.85
Seafood	7.87
Nuts, seeds, and soy	7.87
Legumes	18.20
Sweeteners	7.87

percentage of electricity use. Because of the complicated nature of the food manufacturing industry, we allocated the total water usage of the food industry sector to each food group based on the mass ratio of processed foods. We used this information to estimate the water use for processing of food groups that were not reported in the NWFPA study. Table 2.7 presents estimated water use per kg of each food group reported in the NWFPA study and from the Maupin et al. (2014) study. It was assumed that red meat such as beef, pork and other meats use same amount of processing water per mass processed. Because of the complexity of the system and lack of data, ancillary information including building infrastructure, employees' commutes, accounting or legal services were not included in the inventory processes for food manufacturing life cycle phase.

2.3.1.3 Packaging

Approximately one third of the waste stream in the United States is from product packaging (US Environmental Protection Agency, 2013). Currently, the U.S. population is over 325 million and is constantly increasing (Worldometers, 2017). The total number of meals consumed per day is approximately 975 million (325 million x 3 meals a day per person). Total municipal solid waste (MSW) generation in 2014 was approximately 258 million tons (United States Environmental Protection Agency, 2015). This is the amount of waste generated before combustion with energy recovery, recycling, or composting. It was reported that about 33% of the total MSW is packaging waste (Marsh and Bugusu, 2007). Food packaging waste has been reported to account for two thirds of packaging waste in the United States (Food Packaging Forum, 2017). This ratio was used in estimating the amount of food packaging disposed. Given the absence of more recent data, we assumed that the proportion of food packaging waste to other packaging materials has remained constant. Food packaging waste was estimated based on the percent of each type of packaging in the municipal waste stream. The types of packaging used were obtained from “marketing shares of packaging material (Food Packaging Forum, 2017). This is presented in **Table 2.8**.

Rigid plastic contributes the largest fraction of food packaging materials used at 27%. Packaging for each food group can therefore be determined by multiplying the total municipal solid waste by the percent of this waste that is from packaging waste (258 x 10^6 tons x 0.33 (fraction of packaging waste) = 8.5 x 10^7 tons of packaging waste). That value can then be multiplied by the ratio of packaging waste that is from food packaging (8.5 x 10^7 tons of packaging waste x 2/3 (ratio of food packaging waste) = 5.7 x 10^7 tons of food packaging waste per year. This value was then divided to find the amount of food packaging waste per person per meal and per kilogram. The total amount of food consumed in the “*Usual U.S. Intake: Adults*” dietary scenario based on a 2,000 kcal diet is approximately 1,014 grams. The amount of food consumed in the current consumption diet according to the LAFA database is approximately 1,086 grams. The NHANES daily diet and meals from Dettling et al. (2016) report an amount of food consumed per person daily to be around 1,272 grams. The average daily consumption for these sources is about 1,124 grams, and the average amount of food consumed per meal per person is 375 grams. The amount of food packaging required per person in the U.S is:

$$\frac{5.7\ x\ 10^7\ tons}{365\ days} = 1.56\ x\ 10^5 \left(\frac{tons}{day}\right)$$

$$\frac{1.56\ x\ 10^5 \left(\frac{tons}{day}\right)}{325\ x 10^6\ people * 3 \left(\frac{meals}{day}\right)} = \frac{145\ grams\ food\ packaging}{person\ day}$$

Therefore, for every gram of food consumed, 0.39 grams of food packaging material is disposed. Likewise, for every gram of food packaging material disposed, 2.6 grams of food is consumed. However, these calculations contain packaging usage for beverages including liquor, wine and water, which we do not account for in this study. Thus, we incorporated another resource to estimate packaging materials used for each food group. Marsh and Bugusu (2007) provide information on several food packaging materials and uses. Table 2.8 presents the type of packaging material used for each food group obtained from various studies (Ringblom, 2007; Robertson, 2012; U.S. Packaging & Wrapping LLC, 2017; UN FAO, 2017). We incorporated the available information to assign packaging materials to each food group with its corresponding amount of packaging per kg of product. Table 2.9 presents the type and quantity of packaging material used for each food group. Food packaging was allocated to each food group based on the number of processed products and the ratio of food packaging required with one exception. Corrugated boxes and wood pallets were allocated across all food groups equally. The amount of packaging material recovered from recycling and composting is shown in Table 2.10 These values were incorporated in modelling the recycling rate for each type of food packaging material.

Table 2.8. Type of packaging materials used for each food group.

Food groups	Type of packaging materials
Fruits and Juices	
Whole Fruit	Polymeric films, metal cans[1]
Fruit Juice	Cardboard carton, PET[1]
Vegetables	Flexible packaging, polymeric films, metal cans[2]
Grains	Kraft paper bags with LDPE liner, OTR packages, PVC, LDPE, PET, OPP[1]
Dairy Products	
Milk	Paperboard cartons, glass, plastic containers (HDPE, PET, LDPE)[3]
Dry Milk	Metal cans, aluminum foil, plastic laminates, fiber cans[2]
Ice cream	Glass, plastic (PS, HIPS, PP)[2]
Yogurt	Glass, plastic (PS, HIPS, PP)[2]
Cheese	Plastic (PET, LDPE, OPET, OPA)[2]
Soymilk	Paperboard cartons, glass, plastic containers (HDPE, PET, LDPE)[3]
Protein Foods	
Eggs	Paperboard cartons, molded wood pulp, filler tray[3]
Fish/seafood	Poly bags, laminated films, vacuum bags, thermoforming film, metal cans1
Nuts/Seeds/Soy Products	Thermoplastic, flexible plastic, metals[2]
Poultry	Thermoplastic, non-barrier shrink bags, foam, polymeric films, and paper[3]
Beef	Thermoplastic, foam, polymeric films, and paper[4]
Pork	Thermoplastic, foam, polymeric films, and paper[4]
Other Meats	Thermoplastic, foam, polymeric films, and paper[4]
Beans and Peas	Flexible packaging, polymeric films, metal cans[2]
Oils	Thermoplastic, flexible plastic and paper[2]
Solid Fats	Thermoplastic, flexible plastic and paper[2]
Added Sugars	Thermoplastic and flexible plastic[2]

[1]Robertson, G. L. (2013). Food packaging: principles and practice. Boca Raton, FL, CRE Press.

[2]Ringblom, U. (2007). Selecting the ideal packaging for fruit-based beverages, FRUIT. http://www.fruit-processing.com/docs/FP_5_2007_p.277-281.pdf.

[3]UN FAO (2017). Egg packaging, transport and storage. Agriculture and Consumer Protection, FAO Corporate Document Repository. http://www.fao.org/docrep/005/Y4628E/y4628e05.htm.

[4]U.S. Packaging & Wrapping LLC (2017). A beginner's guide to meat packaging. http://www.uspackagingandwrapping.com/blog/A-Beginner-s-Guide-to-Meat-Packaging.html.

2.3.1.4 Transportation

The average American meal has ingredients from five different countries, not including the U.S. (NRDC, 2007). Weber & Matthews (2008) reported that food transportation represents approximately 11% of food supply chain life cycle GHGEs. In 1997, it was estimated that the total freight of food products from production to retail is about 12,000 t-km per U.S. household per year (Weber and Matthews, 2008). As such, it is important to include transportation when

Table 2.9. Food packaging types and estimated amount of packaging material used for each food group (million tons).

Food Group	Corrugated boxes	Paperboard carton	Kraft paper	Rigid plastic	Flexible plastic	Glass	Wood pallet	Aluminum	Metals
Vegetables	1.28	-	-	-	1.66	-	1.61	-	0.73
Fruits & Juices	0.99	2.07	-	0.57	1.28	-	1.24	-	0.57
Milk and dairy	1.24	3.00	-	0.72	2.41	2.10	1.55	0.50	0.71
Grains	0.94	-	1.08	0.55	1.22	-	1.18	-	-
Red meat	0.51	-	0.58	0.30	0.66	-	0.64	-	-
Beef	0.29	-	0.33	0.17	0.37	-	0.36	-	-
Pork	0.22	-	0.25	0.13	0.29	-	0.28	-	-
Other	0.01	-	0.01	0.00	0.01	-	0.01	-	-
Poultry	0.35	-	0.39	0.20	0.45	-	0.43	-	-
Eggs	0.16	0.33	-	-	0.20	-	0.19	-	-
Fish/Seafood	0.08	-	-	0.05	0.10	-	0.10	-	0.04
Beans/Peas	0.03	-	-	0.02	0.04	-	0.04	-	0.02
Nuts/Seeds	0.05	-	-	0.03	0.07	-	0.07	-	0.03
Fats/Oils	0.48	-	0.55	0.28	0.62	-	0.60	-	-
Sweeteners	0.69	-	-	0.40	0.89	-	0.86	-	-

Table 2.10. Amount of food packaging recycled/recovered and the percent recovery.

MATERIALS	PERCENT OF PACKAGING	PERCENT OF RECOVERY
PAPER AND PAPERBOARDS	34.1	58.8
METALS	7.6	51.3
PLASTICS	11.8	9.4
GLASS	5.2	25.3
TOTAL PACKAGING	100.0	39.9

accounting for the GHGEs of specific food products. In 2016, there were roughly 126 million households in the U.S. (Statista The statistic portal, 2016). This information was used to allocate the transportation impact to each food group based on the number of manufactured products. Table 2.11 presents the estimated distance from production to retail in kg-km for each food group.

2.3.1.5 Retail

The retail sector is a highly concentrated industry with substantial input flows (Scholz, Eriksson and Strid-Eriksson, 2015). Retail stores also consume significant energy and resources that contribute to environmental impacts. The distinct impact streams consist of electricity for store operations (overhead) and refrigeration system, loss of refrigerants due to leakage, natural gas consumption, and water usage (Aquacraft Inc., 2004; ASHRAE, 2012; FMI, 2014; U.S. EPA, 2005; U.S. EPA, 2008). The detailed figures and computations of retail stage inventories are reported in an Appendix. Table 2.12 presents the reference data of a typical grocery retail outlet for the vegetables group as an example. Economic allocation for each food group was estimated using household expenditure data (U.S. BLS, 2012) (Table 2.13). Each refrigerated food group was allocated a share of refrigerated space and a share of total grocery space to account for the refrigeration and overhead burdens, respectively. Each non-refrigerated food group was allocated a share of total grocery space to account for the overhead burdens (including air-conditioning).

Table 2.11. Estimated transportation burden from production to retail for each food group.

Food group	Manufacturing (billion kg)	Transport (kg-km)
Vegetables	36.9	122.0
Fruits & Juices	28.4	93.8
Milk and dairy	35.6	118.0
Grains	27.1	89.6
Red meat	14.8	48.7
Beef	8.2	27.1
Pork	6.4	21.1
Other	0.2	0.5
Poultry	9.9	32.8
Eggs	4.5	14.7
Fish/Seafood	2.2	7.3
Beans/Peas	1.0	3.2
Nuts/Seeds	1.5	5.0
Fats/Oils	13.8	45.6
Sweeteners	19.7	65.0

Table 2.12. Reference data of refrigerated food group at a typical supermarket retail outlet. This table is for the vegetables group as an example.

Composition	Amount	Unit	Note
Total grocery store area	4,270	m^2	FMI, Supermarket facts[1]
Electricity usage	557	$kWh/m^2/year$	ASHRAE 2012 Handbook[2]
Natural gas usage	15.3	$m^3/m^2/year$	ASHRAE 2012 Handbook[2]
Refrigerant load	1,590	kg	US EPA, Supermarket report[3]
Water consumption	2,880	$liter/m^2/year$	Aquacraft Inc. report[4]
Electricity overhead demand	56	%	Energy Star, Building upgrade manual[5]
Electricity refrigeration demand	44	%	Energy Star, Building upgrade manual[5]
Natural gas overhead demand	87	%	Energy Star, Building upgrade manual[5]
Annual refrigerant leak rate	20	%	US EPA, Supermarket report[3]
Fractional total space share	5.6	%	Consumer expenditure survey[6]
Fractional refrigerated space share	10.2	%	Consumer expenditure survey[6]

[1] FMI (2017). FMI Supermarket Facts, Food Marketing Institute. Arlington, VA, USA. https://www.fmi.org/our-research/supermarket-facts.

[2] ASHRAE (2012). ASHRAE Handbook - Heating, Ventilating, and Air-Conditioning Systems and Equipment (I-P Edition); American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.: Online version available at: http://app.knovel.com/hotlink/toc/id:kpASHRAE93/ashrae-handbook-heating/ashrae-handbook-heating.

[3] U.S. EPA (2005). Revised Draft Analysis of U. S. Commercial Supermarket Refrigeration Systems Prepared by ICF Consulting. https://www.epa.gov/sites/production/files/documents/EPASupermarketReport_PUBLIC_30Nov05.pdf.

[4] Aquacraft Inc. (2004). Demonstration of Water Conservation Opportunities in Urban Supermarkets; Water Engineering and Management, Colorado, USA. http://infohouse.p2ric.org/ref/50/49005.pdf.

[5] U.S. EPA (2008). Energy Star Building Upgrade Manual; U.S. Environmental Protection Agency, Office of Air and Radiation 2008 Ed., Washington, D.C., USA. https://www.energystar.gov/sites/default/files/buildings/tools/EPA_BUM_Full.pdf.

[6] U.S. BLS (2012). Consumer Expenditure Survey, 2011, "Table 3. Age of reference person: Average annual expenditures and characteristics, Bureau of Labor Statistics. https://www.bls.gov/cex/2004/Standard/age.pdf.

2.3.1.6 Consumption and End-of-Life

The resources used in the consumer phase: transportation for shopping trips (FHA, 2011; FMI, 2012), home refrigeration (U.S. EIA, 2015), food preparation appliances (UEC, 2017), dishwashing (U.S. EPA 2016), and waste treatment (US Environmental Protection Agency, 2013)

Table 2.13. Estimated food group allocation fraction based on household expenditure data of each food group at retail phase and consumer phase.

Food Group	Supermarket cooling plus refrigeration	Supermarket overhead or Passenger car	Home refrigerator [a]	Food preparation or Dish washer [a]
Vegetables	10.2%	5.30%	14.0%	11.6%
Fruit and Juices	10.8%	5.63%	14.8%	12.3%
Milk and Dairy	13.0%	6.76%	17.8%	14.8%
Grains	2.31%	4.12%	-	9.02%
Red meat	16.0%	8.30%	21.9%	18.2%
Poultry	4.81%	2.50%	6.60%	5.48%
Eggs	1.49%	0.78%	2.05%	1.70%
Fish and Seafood	4.07%	2.12%	5.58%	4.64%
Beans and Peas	0.11%	0.19%	-	0.42%
Nuts and Seeds	0.21%	0.38%	-	0.84%
Fats and Oils	2.10%	1.69%	2.22%	3.69%
Sweeteners	1.24%	2.22%	-	4.86%
Total	*66.4%*	*40.0%*	*85.0%*	*87.6%*

[a] Nonalcoholic and alcoholic beverages represent the remainders of cumulative total.

Table 2.14. Percentage of food loss at each supply chain using USDA ERS LAFA database.

Food Group	**Average food loss rate in year 2010 (%)**			
	Primary loss	**Retail loss**	**Consumer loss**	**Total loss**
Vegetables	31.90	8.48	34.80	59.30
Fruit and Juices	19.80	9.25	36.60	53.90
Milk and Dairy	0.11	11.10	22.50	31.20
Grains	-	12.00	21.80	31.20
Red meat	30.60	4.47	23.90	49.60
Poultry	37.00	3.88	18.80	50.80
Eggs	1.50	9.00	35.00	41.70
Fish and Seafood	-	8.18	34.10	39.50
Beans and Peas	-	6.00	10.00	15.40
Nuts and Seeds	-	6.00	9.18	14.60
Fats and Oils	0.14	19.20	20.70	36.00
Sweeteners	-	11.00	32.60	40.00

were assessed (**Table A-9** in Appendix). We allocated the electricity burden, which was the highest impact driver at the consumer stage, to each food group based on consumer food expenditure data (Table 2.13). For most of the cooking appliances, we adopted the same allocation scheme based on the fraction of expenditure per household rather than disaggregating the energy consumption of cooking appliances to each food group due to of the complexity of cooking. Specific cooking appliances, which were only used for a certain food category, were assigned solely to the specific food group (**Table A-10** in Appendix). Natural gas usage, mostly used in stoves and ovens during food preparation, was not included because data were not available on the fraction of cooking appliances using each type of energy. Thus, we assumed electric ovens and stoves were representative for energy consumption. Water usage for cooking was not included because it is minimal.

2.3.1.7 Food Loss

Food loss contributes substantially to the environmental impact in each life cycle stage. The food supply chain and approximate percent of total food loss derived from USDA LAFA database is shown in Figure 2.2. Food loss was broken into losses at the primary level (post-farm production and processing, e.g. pest damage and weather damage), retail level (e.g. improper handling, food processing, and food safety standards), and consumer level (e.g. losses from cooking and food preparation, excess food preparation, expired foods, spoilage, and plate waste). Table 2.14 gives the food loss estimates at each supply chain stage broken into each food group. The loss rates at each supply chain were applied to each scenario considered in this study.

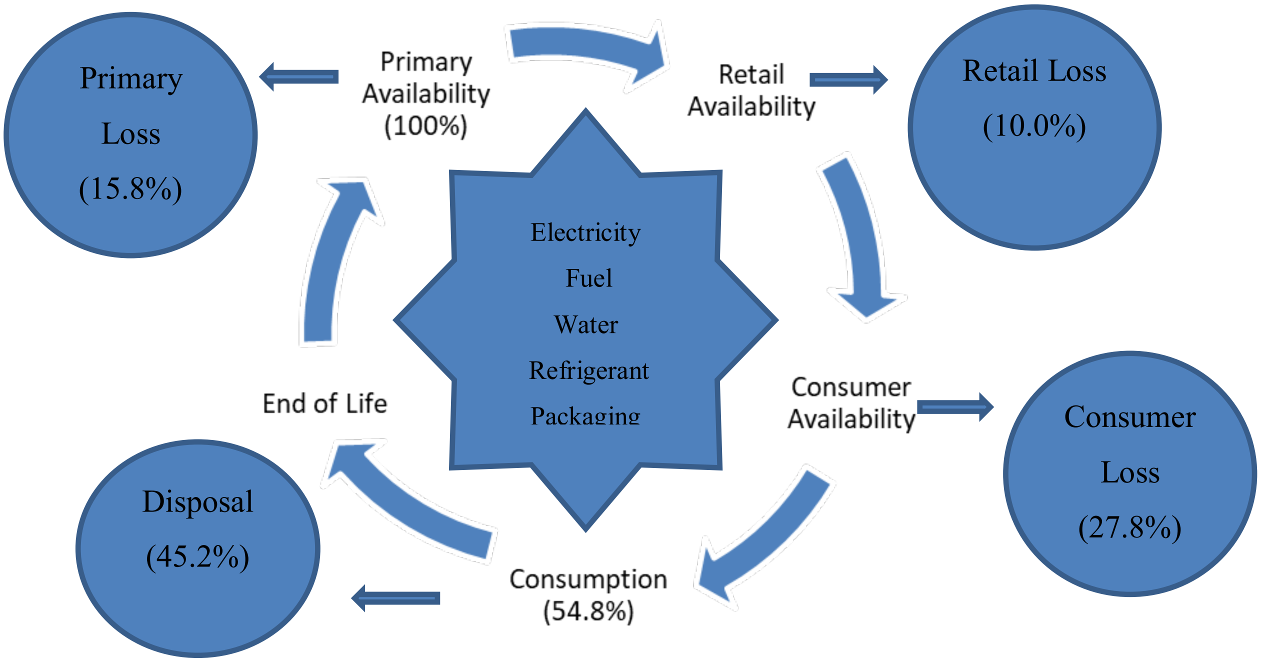


Figure 2.2. Schematic flowchart of food supply chain derived from the USDA LAFA database.

2.3.2 IO-Based LCA Methodology

Input-output (IO) modeling is a general tool used for analyzing environmental consequences by integrating both economic and technical relationships of production systems (Butnar and Llop, 2007). For this study, we used a tiered hybrid LCA to estimate GWP of the food commodity groups. It is based on an environmentally extended national economic input-output (EIO-LCA) model up to the retail gate, and on a process-based LCA model for the retail and consumer phases. SimaPro 8.4 coupled with the Excel interface for the Comprehensive Environmental Data Archive (CEDA) model (Suh, 2005) was used as the computational platform. We chose to link process-based models of the post-manufacturing supply chain to provide the cradle-to-grave perspective with commodity level granularity because the EIO-LCA model lacks coverage beyond the manufacturing stage (Jones, Kammen and McGrath, 2008), and the retail stage burden derived from IO tables cannot be allocated to specific food groups. We analyzed the potential environmental impacts of each food group by mapping food availability and losses across each life cycle stage (Buzby, Farah-Wells and Hyman, 2014). Specific tasks required for this effort included estimation of the economic value (purchase price) for each food group in the diet and meal scenarios and an estimate of the quantity consumed. The mass lost (food waste) and the purchase cost of the associated commodities were aligned due to the character of the EIO-LCA modeling which is based on economic value.

In the IO modeling, each food group was represented using a sectoral analysis based on the U.S. Department of Commerce, Bureau of Economic Analysis commodity groups (U.S. Department of Commerce, 2015). Selective disaggregation of IO sectors such as *fruit and vegetable canning, pickling, and drying; poultry and egg production; animal (except poultry) slaughtering, rendering, and processing* was conducted based on the economic value of the subsectors. Sub-sectors were created by disaggregation so that each new IO sub-sector had only one food group as its main product. For example, when disaggregating the sector *fruit and vegetable canning, pickling and drying* into a fruit subsector and a vegetable subsector, the input value of *vegetable canning, pickling, and drying* to the new disaggregated sub-sector of *fruit canning, pickling, and drying* was set to zero in the revised IO table. Additionally, the input of fruit farming was set to zero for the disaggregated sub-sector of *vegetable canning, pickling, and drying* process, and upstream unit process of *vegetable and melon farming* was set to zero for the disaggregated sub-sector of *fruit canning, pickling, and drying* process. The reference flow (dollars of economic value) of each disaggregated sub-sector was assigned proportionally to its share of the original combined sector. The same concepts and procedures were applied to disaggregate other sub-sectors. Other food groups were assumed to be well approximated by BEA commodity group with respect to production and manufacturing (Table 2.16). The resulting input-output matrix was tested to ensure that the combination of the disaggregated categories provided the same result as the original, aggregated sector.

The purchase price per kg of each food group was estimated from a 4-year average (2012-2015) of annual household expenditure data according to the consumer expenditure survey (Table 2.15, U.S. BLS, 2017). The average number of persons per household was 2.5, and the average annual expenditure for each food group was estimated by the combination of "food at home" expenditure and "food away from home" expenditure in proportion to the reported home and away expenditures. The calculated purchase price (retail price) was multiplied by the CEDA price conversion factor to obtain producer's price which was used in the computational platform to estimate the environmental burdens for the production and processing stage of each food group (that is up to the retail stage, which was modeled using a process model). These steps were needed because the IO tables have emissions reported per dollar expended based on producers'

Table 2.15. Average producer's price per kg of each food group.

Food Group	Expenditure per household[1]	Producer price in dollars per kg	Consumer price in dollars per kg	CEDA price conversion factor
Grains	$471.00	$2.04	$2.04	1.000
Beef	$429.00	$5.54	$6.32	0.876
Pork	$289.00	$4.76	$5.43	0.876
Other Meat	$217.00	$10.40	$11.90	0.876
Poultry	$301.00	$3.44	$3.67	0.937
Eggs	$110.00	$2.66	$2.88	0.924
Fats and Oils	$194.00	$1.50	$1.62	0.925
Vegetables	$659.00	$1.81	$2.08	0.871
Fruits and Juices	$686.00	$2.42	$2.78	0.871
Dairy	$722.00	$2.17	$2.38	0.911
Seafood	$220.00	$8.66	$11.60	0.745
Nuts, seeds, and soy	$39.00	$2.90	$3.14	0.924
Legumes	$19.70	$2.21	$2.52	0.877
Sweeteners	$271.00	$1.36	$1.59	0.856

[1] (U.S. BLS, 2012)

Table 2.16. EIO-LCA commodity sector mapping for each food group.

Food Group	IO Industry Code	EIO-LCA commodity sector mapping
Vegetables	31142B	Vegetable canning, pickling, and drying[1]
Fruit and Juices	31142A	Fruit canning, pickling, and drying[1]
Milk and Dairy	311513	Cheese manufacturing
	31151A	Fluid milk and butter manufacturing
	311514	Dry, condensed, and evaporated dairy product manufacturing
	311520	Ice cream and frozen dessert manufacturing
Grains	311810	Bread and bakery product manufacturing
Red meat	31161A	Animal (beef) slaughtering, rendering, and processing[1]
	31161B	Animal (pork) slaughtering, rendering, and processing[1]
	31161C	Animal (other) slaughtering, rendering, and processing[1]
Poultry	311615	Poultry processing
Eggs	11230B	Egg production[1]
Fish and Seafood	311700	Seafood product preparation and packaging
Beans and Peas	31122A	Soybean and other oilseed processing
Nuts and Seeds	111335	Tree nut farming
Fats and Oils	311225	Fats and oils refining and blending
Sweeteners	31131A	Sugar cane mills and refining

[1] new, disaggregated sectors.

prices in 2002 USD, reported in Table 2.15.

3 Uncertainty Analysis

In LCA, there are several types of uncertainty that can influence the interpretation of the results and place limits on the conclusions (PRé Consultant Inc., 2017):

- Data uncertainty: imprecise or incomplete information of model input and design, for example, the electricity or natural gas consumption at a facility
- Uncertainties about the correctness (representativeness) of the model: conflicting of regional data, allocation choices and methodological uncertainties
- Uncertainties caused by imprecision of the model
- Uncertainties related to systematic or random errors
- Uncertainty associated with the impact assessment framework

The uncertainty associated with the impact assessment framework, specifically the characterization factors, which define the impacts for emissions are not currently available. In this project, the uncertainty in the LCA results was evaluated using a statistical method, Monte Carlo simulation (MCS), available in SimaPro 8.4. This process is rules-based and incorporates probability distributions for variable data that reflect the knowledge and process uncertainty associated with the variable. Briefly, MCS is a method of propagating uncertain knowledge regarding the input of the model to the outputs; in this case, the environmental impacts. This technique is based on the selection of one set of input values that are randomly selected from probability density functions that describe the expected range of input values, followed by calculation of the system impacts, and then repeating this process many times. This analysis is indispensable for establishing defensible metrics for establishing the robustness of the study conclusions. We performed a pairwise comparative MCS approach to avoid amplification of uncertainty associated with shared background processes. The result of the MCS (after 1,000 runs) provided a distribution of the model results, which we used to calculate the 95 percent confidence interval.

The Ecoinvent pedigree matrix for quantifying uncertainty of inputs was applied to unit processes generated from primary data. An inherent uncertainty of ± 15 percent ($\sigma_G 2$ = 1.15), log normal distribution and the pedigree uncertainty score of (3, 2, 2, 1, 1, na) was assigned to all inventory data since, in general, ranges of food intake are not available. Secondary or background data were taken, to the extent possible, from the Ecoinvent v3.3 database (Ecoinvent Centre, 2015); the data quality pedigree provided by the Ecoinvent center for these data was adopted without revision. Unit processes taken from other libraries for which there was no uncertainty information provided, did not have uncertainty specifications added for this project. Therefore, it should be recognized that the confidence bands presented in this section represent a lower bound of the actual uncertainty in the reported impact of the scenario.

4 Results and Interpretation

4.1 Life Cycle Inventory

We compiled LCI data associated with diet and meal scenarios using the USDA Dietary Guidelines and Food Patterns as well as USDA ERS LAFA database and NHANES data. Specific attention was given to differential rates of food loss in the supply chain for various constituents of the diet/meal. Figure 4.1 displays an example of an LCI, distinguishing between the consumption and loss of each food group. The total red meat group represents beef, pork, lamb, and veal. These were treated individually in the specific scenarios presented later. Over the whole life cycle of each food group, the total food consumption and losses aggregated to 1.14 kg and 0.95 kg per person per day, respectively, for the CCP 2,000 kcal diet. Total food losses represented 45% of annual food production by weight. The vegetables group was responsible for the most loss, followed by the fruit/juices group. These two food groups were the source of more than 49% of total food loss for the CCP scenario. The aggregated totals increase to 1.54 kg of projected food consumption and 1.36 kg of food losses per person per day for the scenario of

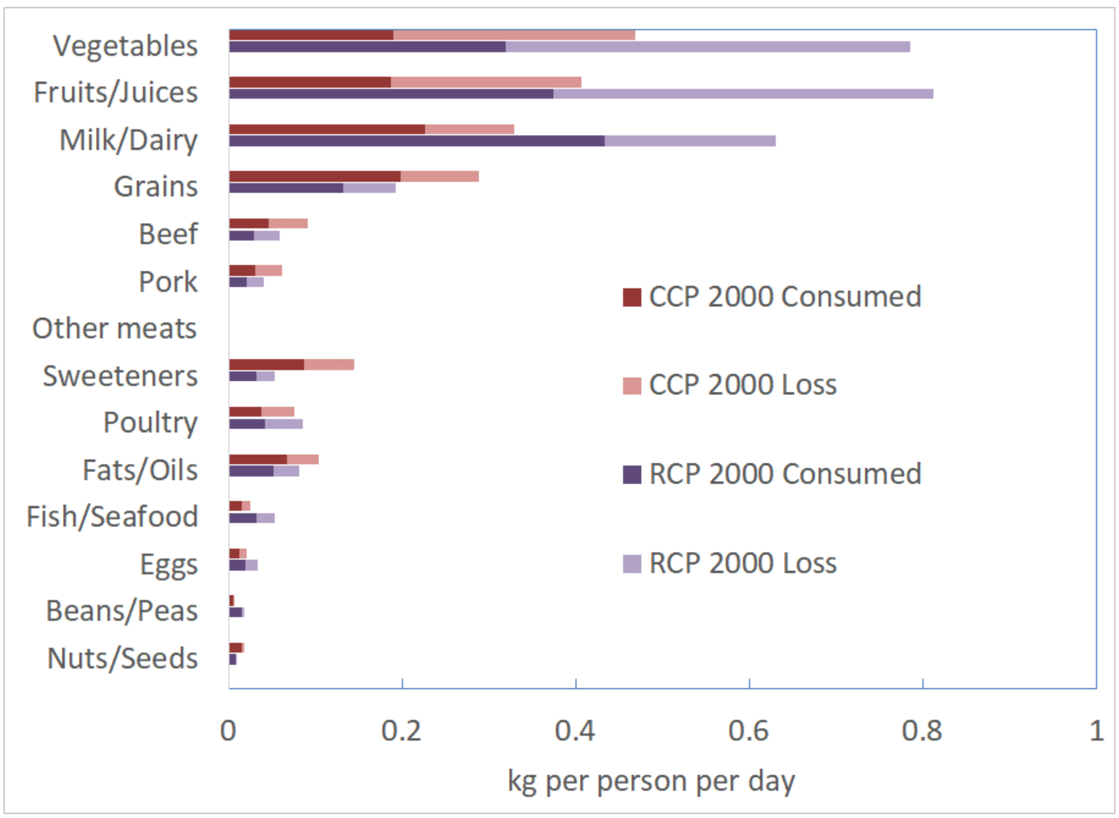


Figure 4.1. Life cycle inventory of food consumption and loss per person per day associated with current food consumption patterns (CCP scaled to 2,000 kcal) versus USDA recommended food consumption patterns (RCP 2,000 kcal).

adopting the USDA 2,000 kcal recommended dietary patterns (RCP) assuming the same fractional loss rates for each food category. Recommended consumption was almost double the CCP for the vegetables, fruit/juices, milk/dairy, and fish/seafood and was higher for the beans/peas, and nuts/seeds/soy groups.

4.2 Life Cycle Impact Assessment Results

4.2.1 Dietary Scenarios

Impact assessment results for the USDA-based dietary scenarios are presented in Figure 4.2 for the water use, land use, and GWP associated with each dietary scenario, relative to the baseline (CCP). The recommended consumption pattern (RCP) had the highest GWP and water use, followed by CCP_S2, which had the greatest land use. The vegetarian diet had the lowest GWP

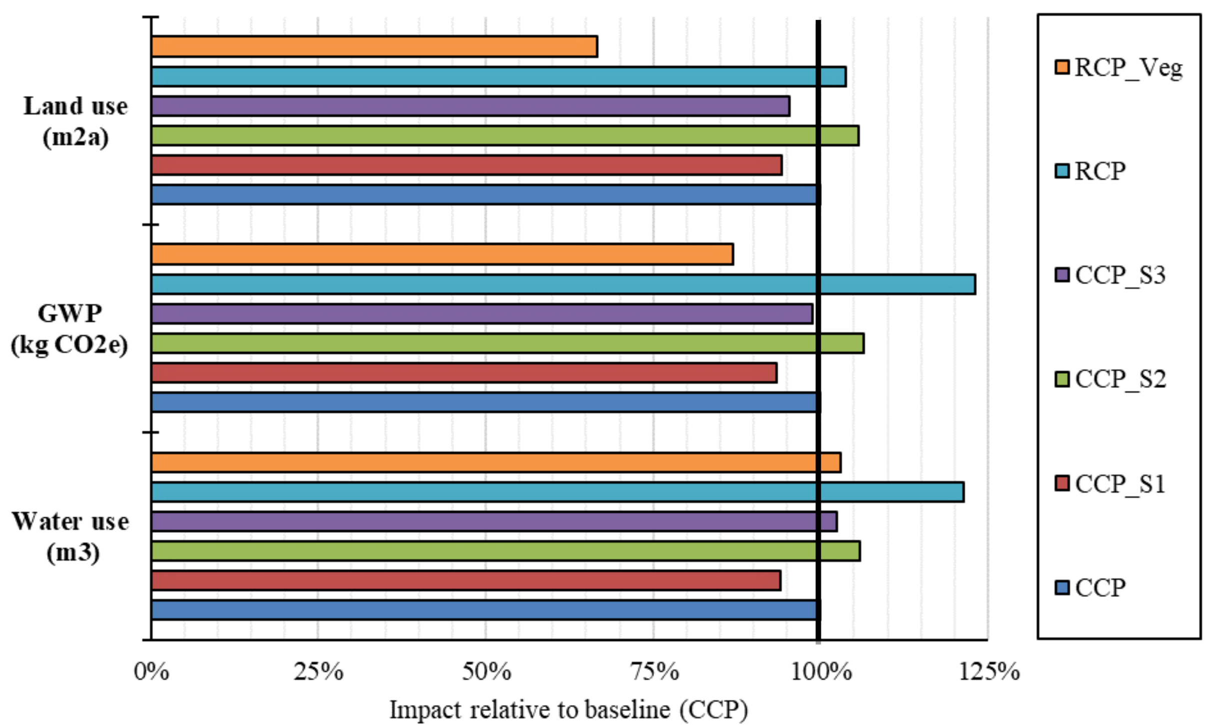


Figure 4.2. Impact assessment results from the process model for the dietary scenarios based on USDA Dietary Guidelines and Food Patterns. Impacts are presented relative to the baseline scenario (100%).

and land use, and the CCP_S1 diet had the lowest water use.

The double pork scenarios (CCP_S2 and CCP_S3) showed an increase in water use relative to the baseline; however, replacing calories from other meats with calories from pork (CCP_S3) reduced GWP and land use when compared to the baseline diet. Removing pork from the baseline diet entirely (CCP_S1) resulted in only a slight reduction in GWP (-5%), water use (-7%), and land use (-6%). The potential to reduce environmental impacts associated with pork consumption – as represented by CCP_S1 – was minimized via the increased consumption of other red meats, which have higher impacts per kg consumed than pork.

Despite delivering approximately equivalent calories, the USDA recommended diet (RCP) had higher impacts associated with consumption relative to current consumption (CCP) for each of the three categories assessed. This result can be explained by the energy density of the foods within each diet. The RCP diet recommends foods that are less energy dense (fewer calories per kg of food) than in the CCP scenario. The RCP diet had approximately double the servings of fruits, dairy products, and legumes than the CCP diet, whereas the CCP diet had higher levels of fats, sugars, and red meats, which are much more energy dense. As a result, the RCP diet had 44% more food mass than the CCP. The LCIA results for each food group along with its energy density are shown in Table 4.1.

With the exception of the vegetarian diet, the environmental impacts associated with each dietary

Table 4.1. Water use, land occupation, and GWP associated with the consumption of 1kg of each food group, along with its average energy density. Environmental impact/energy density values are shaded from green (lowest) to red (highest).

	Water use ***(m^3/kg)***	**Land occupation** ***(m^2a/kg)***	**GWP** ***(kg CO_2-eq/kg)***	**Energy density** ***(kcal/kg)***
Fruit & Juices	0.36	0.95	3.92	527
Vegetables	0.13	0.95	4.89	624
Grains	0.47	5.00	3.69	3660
Milk & Dairy	0.09	2.61	5.73	1080
Eggs	0.04	0.19	3.96	1440
Fish & Seafood	0.14	4.19	16.13	1190
Nuts & Soy	0.67	4.75	7.44	6130
Poultry	0.63	5.42	10.84	2290
Beef	0.95	36.66	50.45	3030
Pork	1.11	14.26	27.20	2720
Other meats	6.61	0.06	12.52	2610
Beans & Peas	0.13	4.50	16.28	1360
Fats & Oils	0.52	7.75	7.41	8612
Sweeteners	0.32	2.74	4.06	3810

scenario were dominated by meat consumption, with beef being the single greatest source of GWP and land use in a majority of the diets (Figure 4.3). The largest contributor to the GWP of the vegetarian diet was dairy; however, it was the second largest contributor to GWP after meat for all other diets and represents between 31% (RCP) and 47% (CCP_S2) of the impact category. The top contributors to GWP following meat and dairy were vegetables, fruits, and fats/oils, depending the diet.

The major contributor to water use varied from one diet to another. For the scenarios with increased pork (CCP_S2/S3), pork was the single largest contributor to water use, followed by grains, and then fruits. Water use associated with the CCP and CCP_S1 scenarios was primarily attributable to grains, followed closely by fruits. Whereas the water use associated with the USDA recommended diet and its vegetarian adaptation (RCP_Veg) was dominated by fruits, representing 32% and 38% of impact category, respectively. The next highest contributor in either diet was grains, which contribute 15% of the water use in RCP and 18% in RCP_Veg – less than half the water use of fruits.

Land use associated with the carnivorous dietary scenarios was also dominated by meat consumption, primarily from beef, which accounts for 26 – 41% of the land use in those scenarios. Dairy was also a significant contributor to land use in each of the diets and was the single greatest contributor in both of the USDA recommended diets. The land use associated with grains was also significant, ranging from 15% of the RCP scenario to 22% of RCP_Veg. Fruits and vegetables did not affect the land use category as much as water use and GWP. This is largely due to the land footprint of beef, which overshadows much of the contribution from other food groups.

The IO and process model GWP results are shown side-by-side in Figure 4.4. The IO-based analysis showed similar trends to the process-based analysis with one notable exception: the process-based analysis showed a larger GWP for the CCP_S3 dietary scenario relative to the S1 alternative. This trend was reversed in the IO-based based results; however, both methodologies suggest a decline in GWP for the S1 and S3 diets relative to the baseline. Relatively narrower gaps in confidence intervals were observed under the IO-based analysis because there are fewer uncertain input values and parameters than in the process-based model.

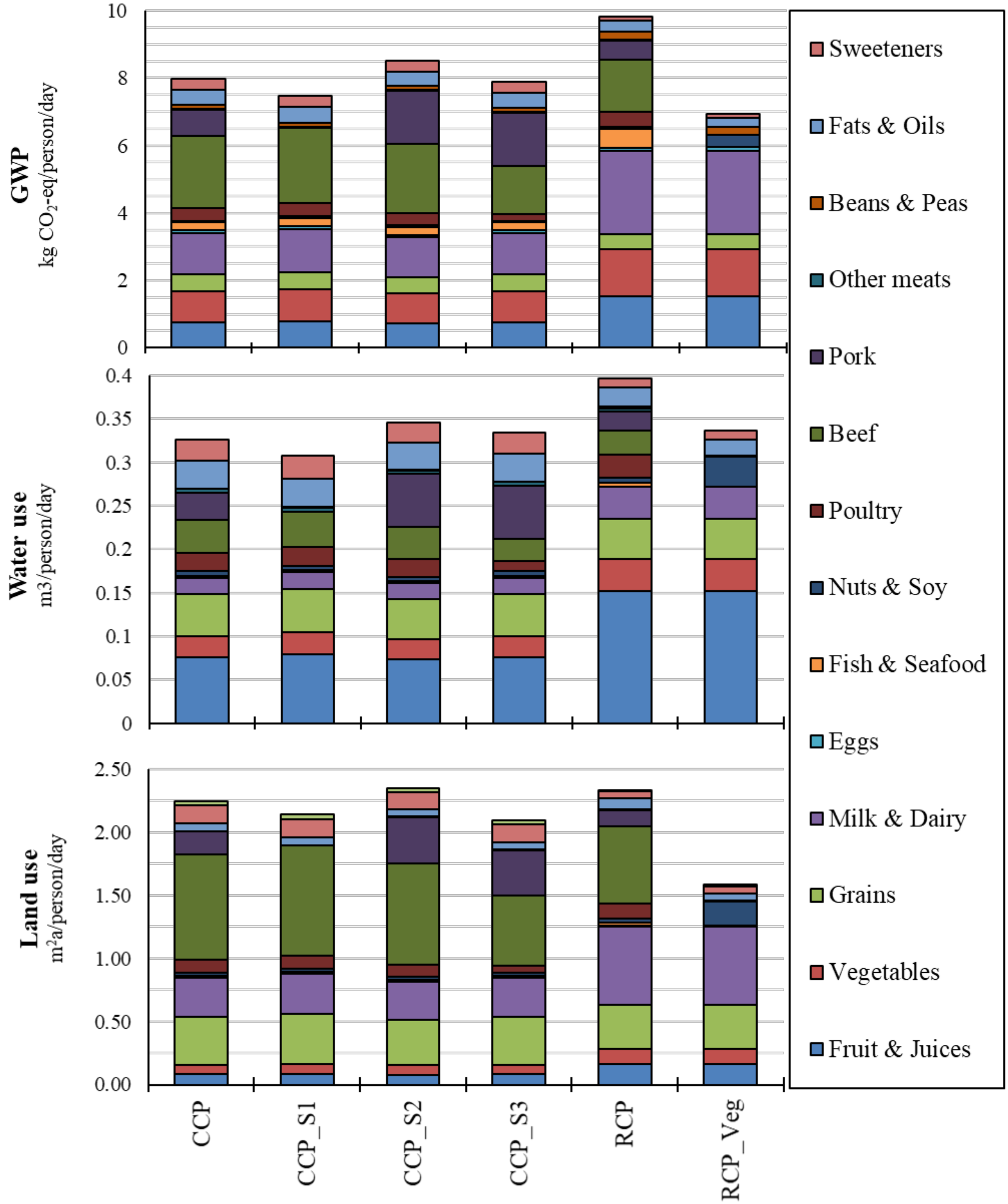


Figure 4.3. Life cycle impact assessment results for the USDA-related dietary scenarios.

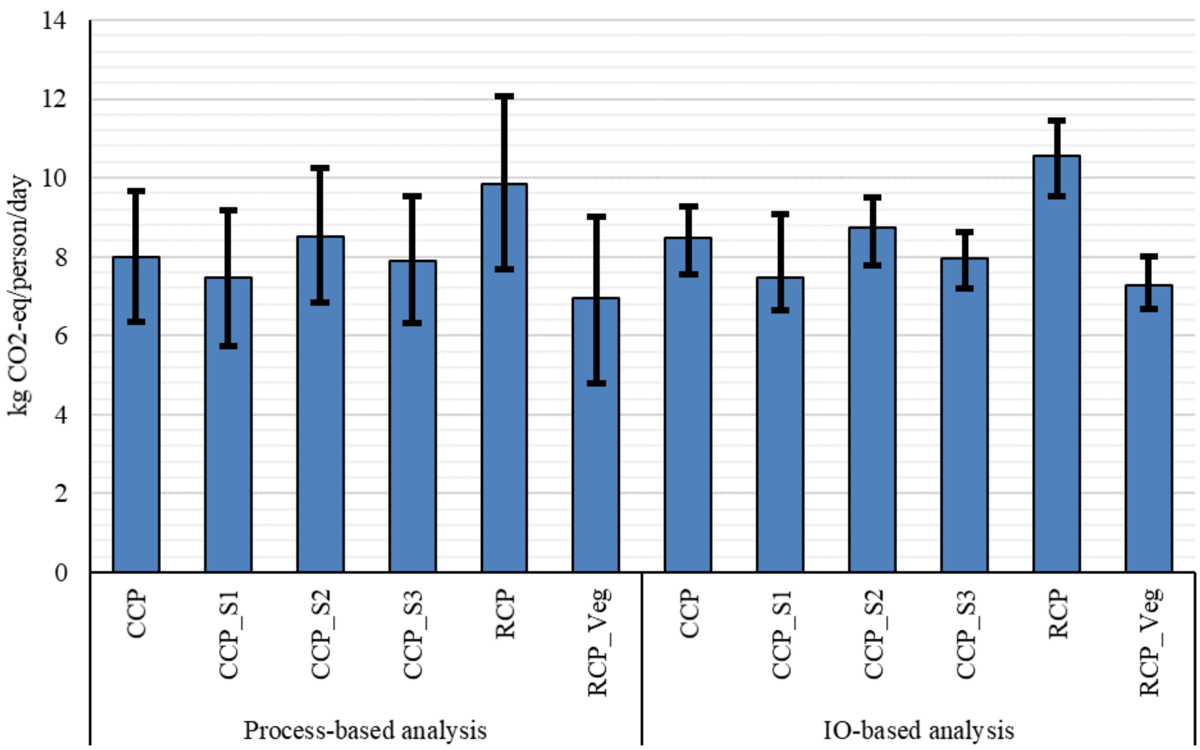


Figure 4.4. Comparative GHG emissions of multiple dietary scenarios based on USDA Dietary Guidelines and Food Patterns associated with process-based analysis and IO-based analysis. Minimum and maximum bars shown in the figure in grey represent 95% confidence intervals.

4.2.2 Dietary Scenarios on LAFA Database

Impact assessment results for the LAFA-based dietary scenarios are presented in Figure 4.5 for the water use, land use, and GWP associated with each dietary scenario, relative to the baseline (LAFA_Current). The LAFA_S2 scenario (increased pork replacing calories from all food groups) had the highest impact in all three categories and the vegetarian adaption has the lowest. The double pork scenarios (LAFA_S2 and LAFA_S3) showed an increase in water use relative to the baseline.

The impact contributions of individual food groups were similar to those discussed with regard to the USDA-based scenarios, albeit with a few notable exceptions. The baseline LAFA diet (LAFA_Current) relies on poultry products for a larger portion of its calories than the CCP, which has relatively higher levels of fruits and vegetables. Poultry has higher impact potentials in each category assessed (per kg consumed), which results in a greater portion of the environmental impacts from meat than in the USDA diets. The individual contributions of each food group to

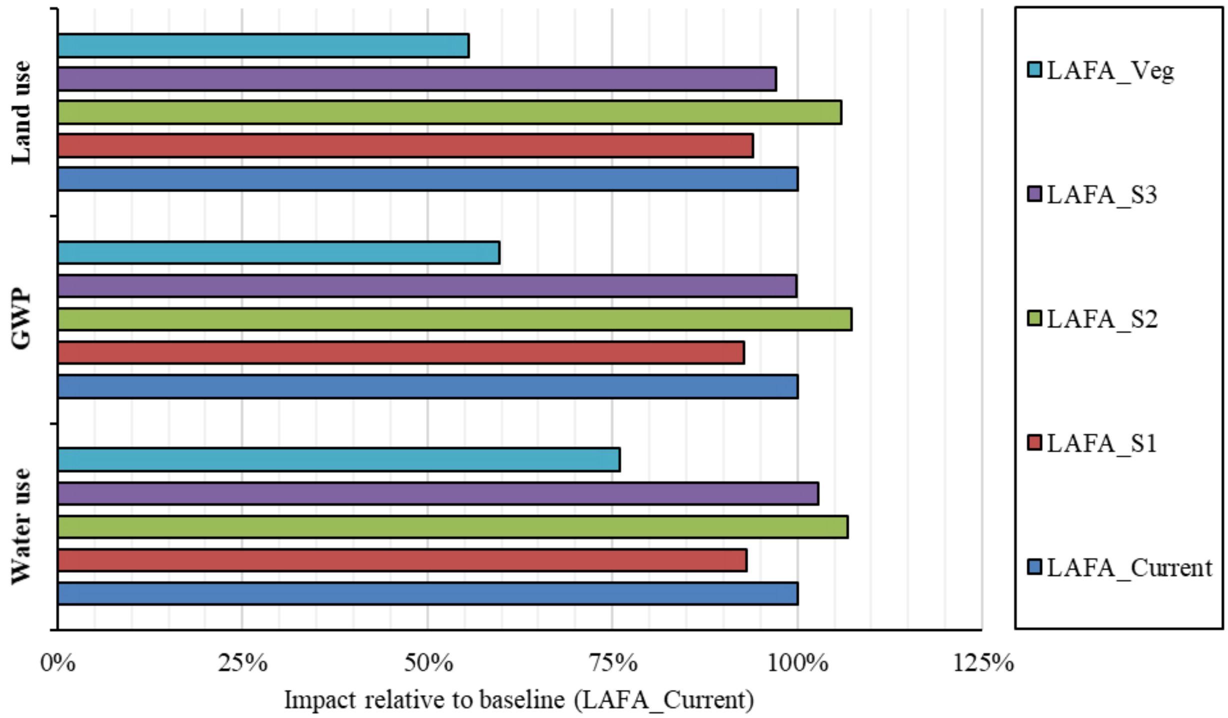
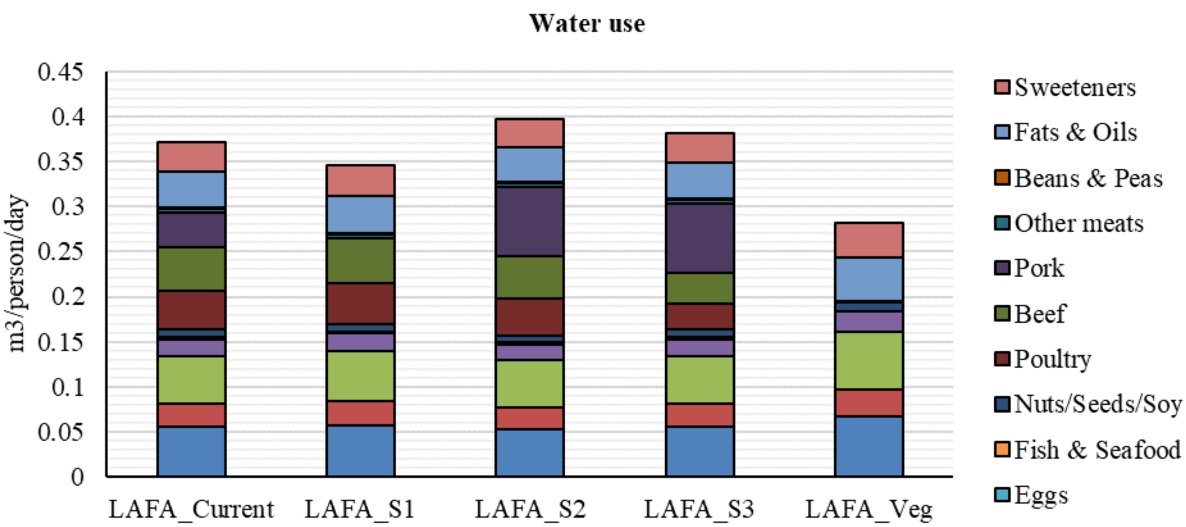
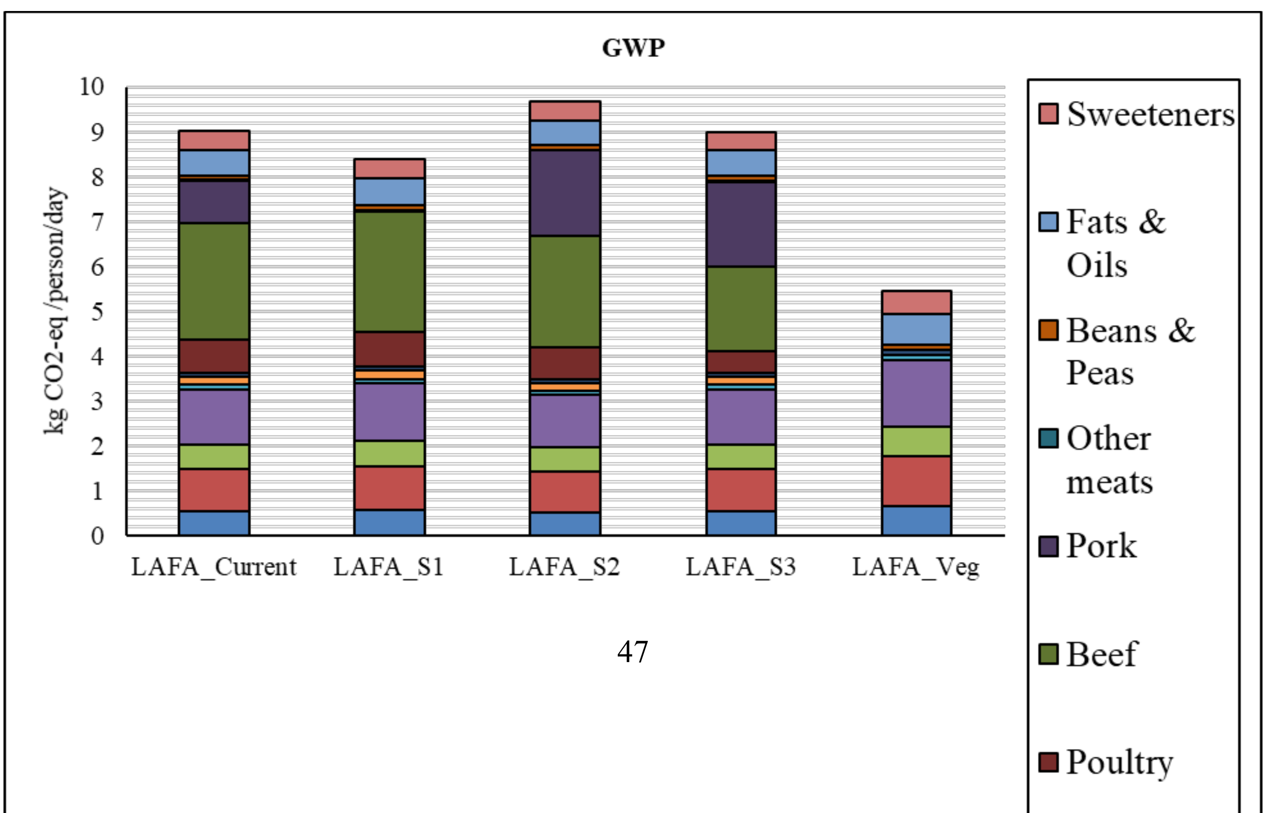


Figure 4.5. Impact assessment results from the process model for the dietary scenarios based on the LAFA database. Impacts are presented relative to the baseline scenario.

the environmental impacts associated with each LAFA-based diet are shown in Figure 4.6. A comparison of estimated GHG emissions determined from both process-based and IO-based analyses are presented in Figure 4.7. The relative agreement between the two modeling methods supports the robustness of the conclusions – from a comparative perspective. The different methods are expected to give different numerical estimates because the inherent system boundaries are different. The smaller error bars associated with the IO model are a consequence of fewer unit processes in the background economic model having assigned uncertainty.


Water use
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
m3/person/day
LAFA_Current
LAFA_S1
LAFA_S2
LAFA_S3
LAFA_Veg
Sweeteners
Fats & Oils
Beans & Peas
Other meats
Pork
Beef
Poultry
Nuts/Seeds/Soy
Fish & Seafood
Eggs


GWP
10
9
8
7
6
5
4
3
2
1
0
kg CO2-eq /person/day
LAFA_Current
LAFA_S1
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LAFA_S3
LAFA_Veg
Sweeteners
Fats & Oils
Beans & Peas
Other meats
Pork
Beef
Poultry

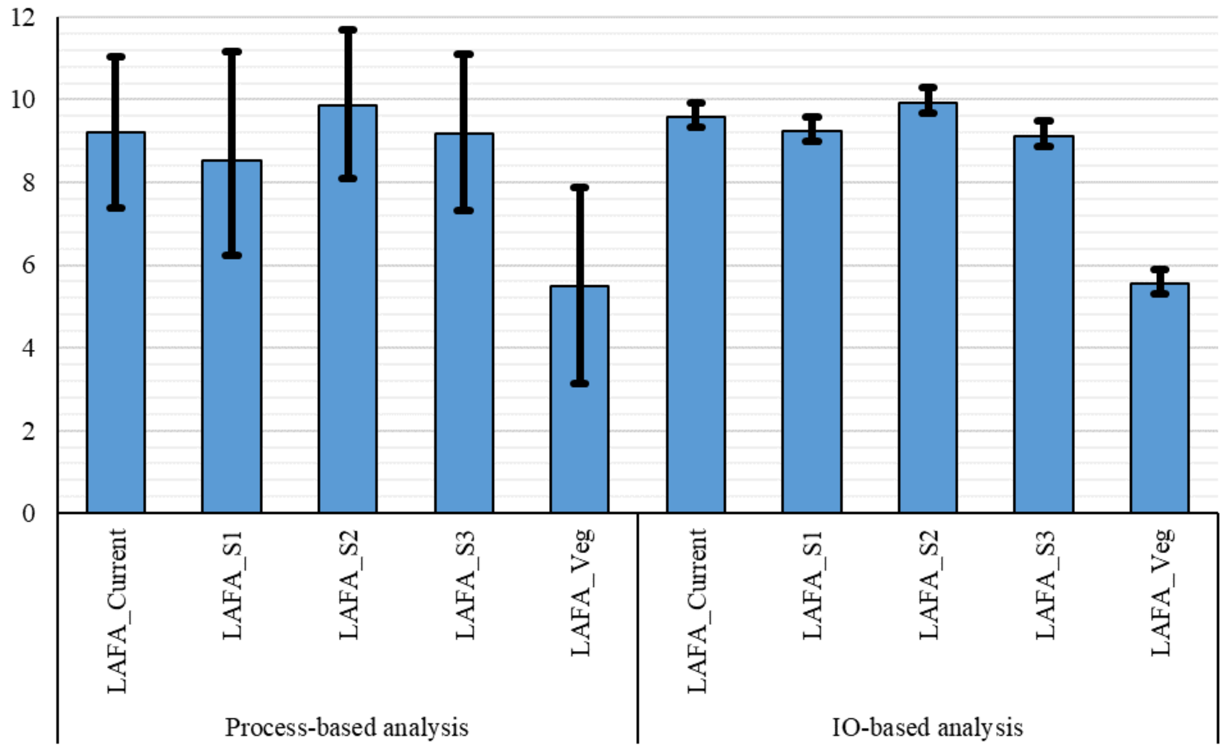

Figure 4.7. Comparative GHG emissions of multiple dietary scenarios based on LAFA database associated with process-based analysis and IO-based analysis.

4.2.3 Vegetarian Diets

When we analyzed the vegetarian diets (LAFA_Veg and RCP_Veg), we found a discrepancy that requires further investigation. The GWP of the LAFA-oriented vegetarian diet (LAFA_Veg) was substantially lower than the USDA recommended vegetarian diet (RCP_Veg), despite having 20% more caloric energy. This result can be explained by the constituents of the two vegetarian diets. The USDA recommended vegetarian diet had more than double the fruits/juices, nearly double the amount of milk/dairy, and one-third more vegetables than the LAFA_Veg diet. Whereas the LAFA-oriented vegetarian diet had more grains, fats/oils, and sweeteners, which are lower impact per calorie than fruits, vegetables, and dairy products. The contributions to the GWP of the two vegetarian diets are shown in Figure 4.8.

4.2.4 Meals with and without Pork from NHANES

Figure 4.9 compares the environmental impacts associated with consuming meals with and without pork for breakfast, lunch, and dinner. The four food groups that contributed the most GWP in pork-free meals were: vegetables, fish/seafood, poultry, and beef. Pork and pork-free meals did not display dramatic differences in total GWP, but pork-free meals did have a slightly

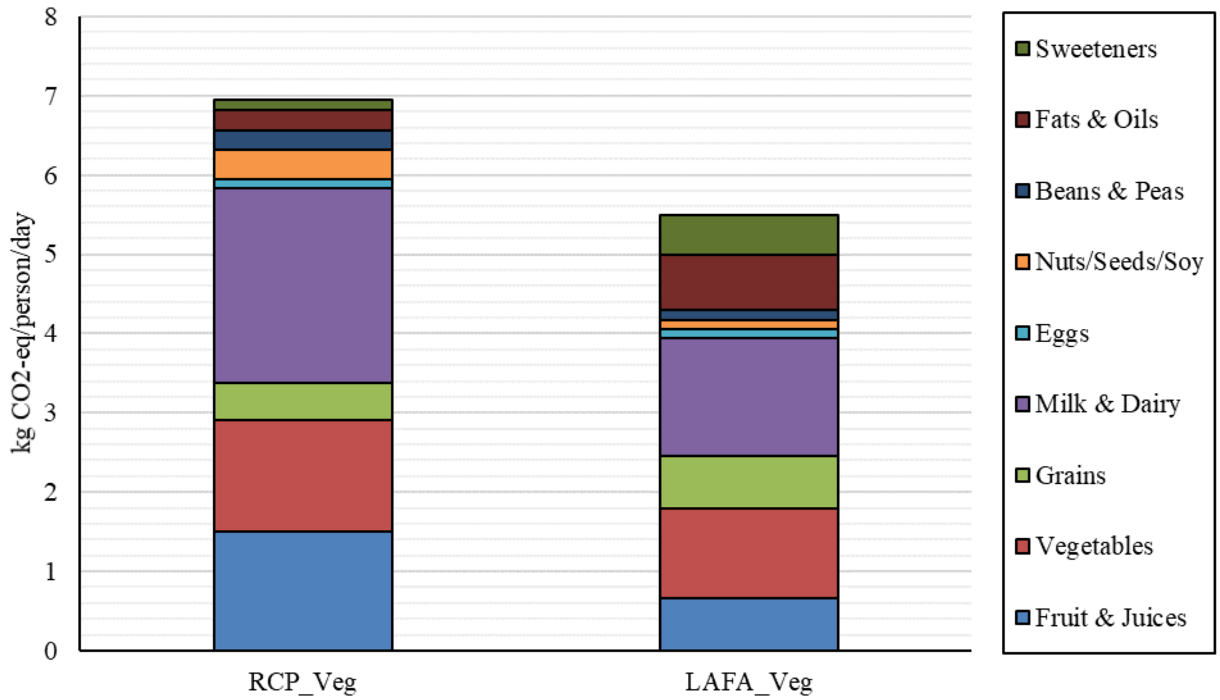

Figure 4.8. Comparative GHG emissions of USDA recommended vegetarian diet versus LAFA-oriented vegetarian diet using process-based analysis.

higher GWP, ranging from 1.4% to 2%. Any potential for impact reduction from consuming meals without pork was offset by the calories from increased beef and poultry consumption, although primarily beef, which has a higher GWP per kg consumed than the pork it displaces.

The three dominant food groups that contributed the most to land use impacts in pork-free meals were grains, poultry, and beef. Pork-free breakfast, lunch and dinner displayed higher land use impacts than their pork-containing counterparts. A pork-free meal resulted in an 8.4%, 6.4% and 6.0% increase of land occupation compared to a pork-containing meal for breakfast, lunch and dinner, respectively. The major contributor to this result was increased consumption of beef.

Water use impacts associated with pork-free meals were similar to land use, with the top three contributing food groups being grains, poultry, and beef. Irrigation water was the primary driver of this result, as feed crops require significant water use. Pork-free breakfast, lunch and dinner showed lower water use impacts than their counterpart meals containing pork. The reductions were 4.1%, 3.5% and 3.3% for breakfast, lunch and dinner, respectively.

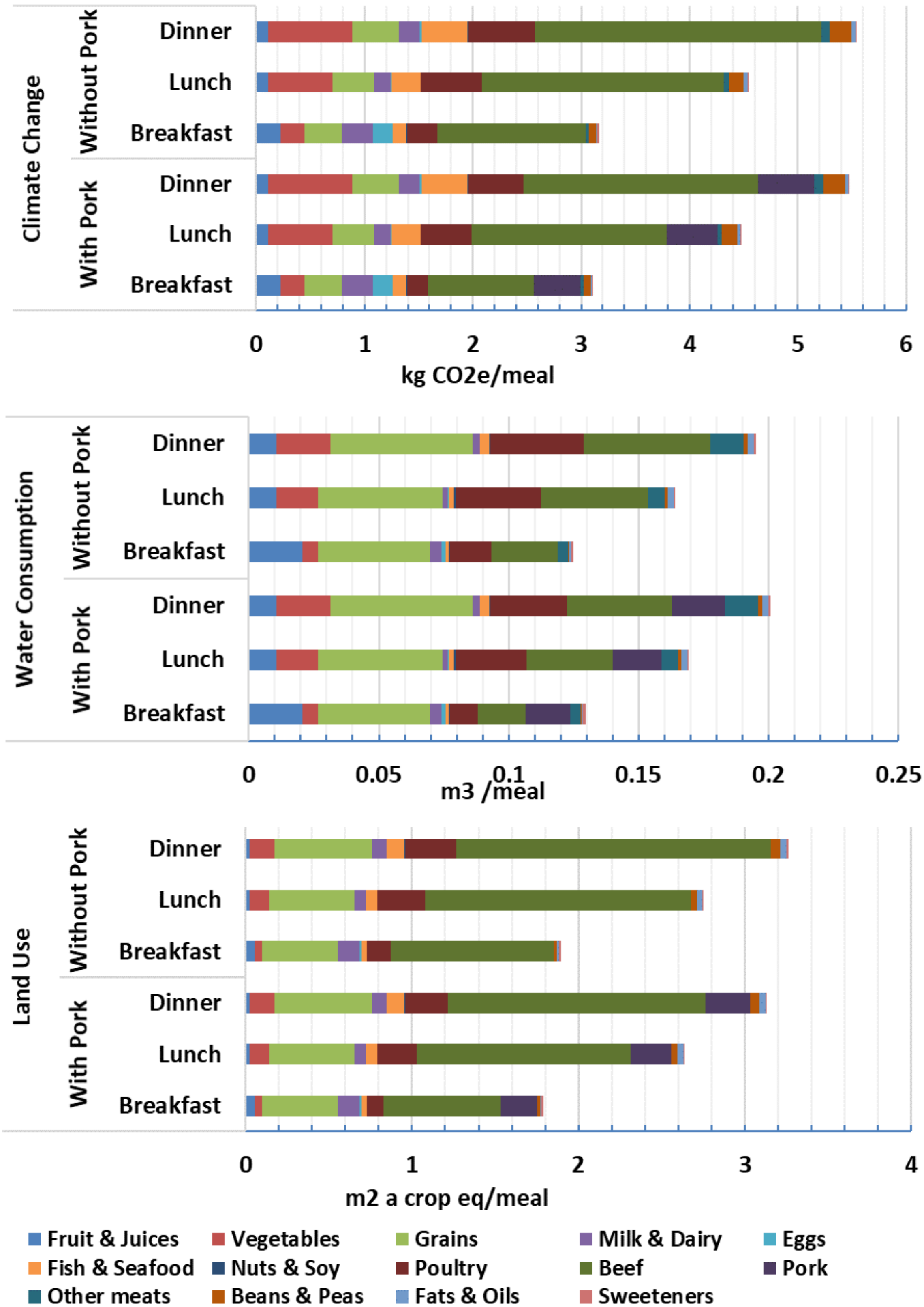

Figure 4.9. Environmental impacts associated with meals with and without pork.

4.3 Uncertainty Analysis and Pairwise Comparison

In addition to the statistical evaluation of results presented above (Figure 4.4 and Figure 4.7), Figure 4.10 presents simulation results of pairwise comparison of meals as a percentage of 1,000 MCS runs. Meals with pork performed better when analyzing GWP in 80% of the simulations compared to their pork-free counterparts. When comparing land occupation impact, 100% of the simulations of pork-containing meals performed better compared to pork-free meals. On the other hand, pork-free meals performed better than pork-containing meals in nonrenewable fossil depletion. These results indicate that removing pork from the diets by substituting beef and poultry has detrimental effects on global warming and land occupation impact. On the other hand, removing pork from the diets neutral on water use and increases fossil depletion health impacts. These results differ from those reported by Dettling et al. in which they report that meat-free meals have superior environmental performance in all categories. There are two primary reasons for these differences. The first is that this study is performed based on equivalent calories rather than equivalent mass and some of the pork-free meals in this study have non-pork meats as substitutes. In addition, the earlier study does not include detailed estimates of retail and

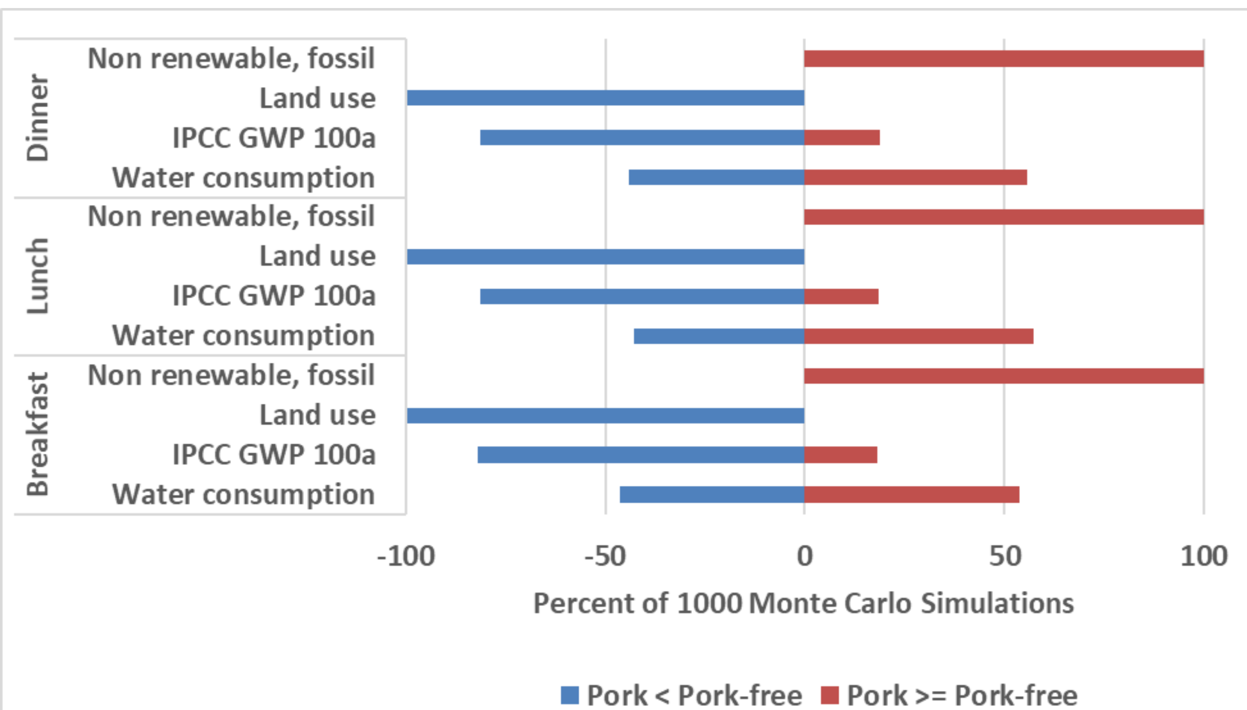

Figure 4.10. Pairwise Monte Carlo comparison of pork-containing current meals versus pork-free meals that presents which scenario is better or equal to the other in impact categories.

consumption burdens associated with each specific food group.

5 Conclusions

The goal of this study was to perform a life cycle assessment of greenhouse gas emissions, land occupation, and water use impact of a diet/meal that includes nutritionally equivalent pork and pork-free diets/meals. A combination of life cycle inventory compilation, life cycle impact assessment, and human health impact of dietary/meal choices with and without pork were reported. Specific attention was paid to differential rates of food loss in the supply chain for different ingredients of the diets/meals. Several primary conclusions were drawn from the study. Pork-containing meals perform better in perspective of global warming potential in 80% of the simulations compared to pork-free meals in which pork is replaced iso-calorically with beef and chicken. Meals with pork also perform better in land occupation than pork-free meals in 100% of the simulations. On the other hand, pork-free meals performed better than pork-containing meals in regarding fossil depletion and were neutral regarding water consumption.

These results combined with dietary scenarios make it evident that the iso-caloric increase of daily pork consumption in the diet/meal has the potential to have beneficial effects on GHGEs and land use impacts, but it also has potential to increase water use and non-dietary human health impacts. In conclusion, dietary or meal choices have unavoidable impacts on GHGEs, land use, water use, and human health, but the effects of choices of diets/meals have dissimilar influences on impact categories. These trade-offs imply that there are few simple solutions when trying to choose foods to lessen impacts on the environment and human health with diets/meals choices. These conclusions do not, of course, include an accounting of all the potential effects of differences in nutritional content among the many choices. Some aspects of dietary choices on health outcomes are presented in the appendix (6.2).

Food losses at the retail and consumer levels represent most of the avoidable food waste except for non-avoidable shrinkage during cooking. Avoidable food loss in the consumer phase can be reduced by changes in consumers' behavior. This suggests that efforts to reduce perishable food loss through improved preservation, reduced transit times, and possibly local, seasonal production are also important in order to reduce the unintended environmental consequences.

6 Appendix

6.1 Calculation Approaches

6.1.1 Food Loss Estimation Using USDA LAFA Database

Food loss at consumer level:

$$Consumer\ loss = \frac{Consumption}{(100\% - \%\ loss\ at\ consumer\ level)} - Consumption$$

Food loss at retail level:

$$Retail\ loss = \frac{(Consumption + consumer\ loss)}{(100\% - \%\ loss\ at\ retail\ level)} - (Consumption + consumer\ loss)$$

Food loss at primary level:

$$Total\ food\ loss = consumer\ loss + retail\ loss + primary\ loss$$

$$Primary\ loss = \frac{(Consumption + consumer\ loss + retail\ loss)}{(100\% - \%\ loss\ at\ primary\ level)} - (Consumption + consumer\ loss + retail\ loss)$$

6.1.2 Estimation of retail and consumer burdens for the vegetables group as an example at a typical supermarket.

Composition	Symbol	Composition	Symbol
Total grocery store area	$A_{G,T}$	Annual electricity burden	$V_{E,G}$
Natural gas usage	$C_{N,A}$	Electricity burden per kg displayed	$V_{E,M}$
Water consumption	$C_{W,A}$	Annual natural gas burden	$V_{N,G}$
Natural gas overhead demand	$D_{N,O}$	Natural gas burden per kg displayed	$V_{N,M}$

Annual refrigerant leak rate	$LR_{R,A}$	Annual refrigerant burden	$V_{R,G}$
Fractional total space share	$FS_{V,T}$	Refrigerant burden per kg displayed	$V_{R,M}$
Annual natural gas burden	$V_{N,G}$	Annual water usage	$V_{W,G}$
Annual water usage	$V_{W,G}$	Water usage per kg displayed	$V_{W,M}$

Natural gas burden in a typical supermarket:

$$V_{N,G} = C_{N,A} \times A_{G,T} \times D_{N,O} \times FS_{V,T}$$

Water usage burden in a typical supermarket:

$$V_{W,G} = C_{W,A} \times A_{G,T} \times FS_{V,T}$$

Passenger car distance traveled:

$$Travel\ distance\ \left(\frac{km}{kg}\right) = 104\left(\frac{trip}{year}\right) \times 10.9\left(\frac{km}{trip}\right) \times \frac{Allocation\ fraction\ of\ vegetables\ group}{Retail\ purchased\ \left(\frac{kg}{household * year}\right)}$$

Home refrigerator electricity usage:

$$Electricity\ usage\ \left(\frac{kWh}{kg}\right) = 1{,}250\left(\frac{kWh}{year}\right) \times \frac{Refrigeration\ fraction\ of\ vegetables\ group}{Retail\ purchased\ \left(\frac{kg}{household * year}\right)}$$

6.1.3 Store Count by Grocery Channels

Channels	Number of stores	Area per store	Supermarket equivalent area-weighted number of stores
Supermarket	32,030	4,270 m^2	32,030
Mass Merchandiser	7,270	3,900 m^2	6,640
Convenience	185,980	430 m^2	18,870
Total	225,280	4,270 m^2	57,540

Electricity burden per kg of vegetables displayed:

$$V_{E,M}\left(\frac{kWh}{kg}\right) = V_{E,G}\left(\frac{kWh}{year}\right) \times \frac{Supermarket\ equivalent\ area\ weighted\ number\ of\ stores}{Total\ vegetables\ displayed\ \left(\frac{kg}{year}\right)}$$

Natural gas burden per kg of vegetables displayed:

$$V_{N,M}\left(\frac{m^3}{kg}\right) = V_{N,G}\left(\frac{m^3}{year}\right) \times \frac{Supermarket\ equivalent\ area\ weighted\ number\ of\ stores}{Total\ vegetables\ displayed\ \left(\frac{kg}{year}\right)}$$

Refrigerant burden per kg of vegetables displayed:

$$V_{R,M}\left(\frac{kg}{kg}\right) = V_{R,G}\left(\frac{kg}{year}\right) \times \frac{Supermarket\ equivalent\ area\ weighted\ number\ of\ stores}{Total\ vegetables\ displayed\ \left(\frac{kg}{year}\right)}$$

Water usage per kg of vegetables displayed:

$$V_{W,M}\left(\frac{liter}{kg}\right) = V_{W,G}\left(\frac{liter}{year}\right) \times \frac{Supermarket\ equivalent\ area\ weighted\ number\ of\ stores}{Total\ vegetables\ displayed\ \left(\frac{kg}{year}\right)}$$

Table A-8. Allocated burdens in a typical supermarket and allocated burdens per kg displayed across all other food groups.

Food Group	Input	Annual burden in a typical supermarket		Burden per kg displayed	
Fruit and Juices	Electricity	184,446	kWh/year	3.52e-01	kWh/kg
	Natural gas	3,202	m^3/year	6.44e-03	m^3/kg
	Refrigerant	34.5	kg/year	6.75e-05	kg/kg
	Water	6.92e+05	liter/year	1.319	liter/kg
Vegetables	Electricity	173,808	kWh/year	2.58e-01	kWh/kg
	Natural gas	3,018	m^3/year	4.72e-03	m^3/kg
	Refrigerant	32.5	kg/year	4.82e-05	kg/kg
	Water	5.67e+05	liter/year	0.842	liter/kg
Milk and Dairy	Electricity	221,612	kWh/year	3.44e-01	kWh/kg
	Natural gas	3,848	m^3/year	6.30e-03	m^3/kg
	Refrigerant	41.4	kg/year	6.43e-05	kg/kg
	Water	8.31e+05	liter/year	1.291	liter/kg
Grains	Electricity	77,506	kWh/year	1.58e-01	kWh/kg
	Natural gas	2,345	m^3/year	5.03e-03	m^3/kg
	Refrigerant	7.3	kg/year	1.50e-05	kg/kg
	Water	5.07e+05	liter/year	1.034	liter/kg
Beef	Electricity	150,882	kWh/year	1.05e+00	kWh/kg
	Natural gas	2,620	m^3/year	1.92e-02	m^3/kg
	Refrigerant	28.2	kg/year	1.96e-04	kg/kg
	Water	5.66e+05	liter/year	3.929	liter/kg
Pork	Electricity	118,379	kWh/year	1.05e+00	kWh/kg
	Natural gas	2,055	m^3/year	1.92e-02	m^3/kg
	Refrigerant	22.1	kg/year	1.96e-04	kg/kg
	Water	4.44e+05	liter/year	3.929	liter/kg
Poultry	Electricity	81,930	kWh/year	4.70e-01	kWh/kg
	Natural gas	1,423	m^3/year	8.61e-03	m^3/kg
	Refrigerant	15.3	kg/year	8.78e-05	kg/kg
	Water	3.07e+05	liter/year	1.763	liter/kg
Eggs	Electricity	25,422	kWh/year	3.13e-01	kWh/kg
	Natural gas	441	m^3/year	5.73e-03	m^3/kg
	Refrigerant	4.75	kg/year	5.84e-05	kg/kg
	Water	9.54e+04	liter/year	1.173	liter/kg
Fish and Seafood	Electricity	69,357	kWh/year	1.72e+00	kWh/kg
	Natural gas	1,204	m^3/year	3.15e-02	m^3/kg
	Refrigerant	13.0	kg/year	3.22e-04	kg/kg
	Water	2.60e+05	liter/year	6.458	liter/kg
Beans and Peas	Electricity	3,640	kWh/year	2.18e-01	kWh/kg
	Natural gas	110	m^3/year	6.97e-03	m^3/kg
	Refrigerant	0.35	kg/year	2.07e-05	kg/kg
	Water	2.38e+04	liter/year	1.427	liter/kg
Nuts and Seeds	Electricity	7,202	kWh/year	2.72e-01	kWh/kg
	Natural gas	218	m^3/year	8.69e-03	m^3/kg
	Refrigerant	0.68	kg/year	2.58e-05	kg/kg
	Water	4.71e+04	liter/year	1.780	liter/kg
Fats and Oils	Electricity	48,842	kWh/year	1.91e-01	kWh/kg
	Natural gas	1,192	m^3/year	4.93e-03	m^3/kg
	Refrigerant	6.66	kg/year	2.61e-05	kg/kg

Table A-8. Allocated burdens in a typical supermarket and allocated burdens per kg displayed across all other food groups.

Food Group	Input	Annual burden in a typical supermarket		Burden per kg displayed	
	Water	2.58e+05	liter/year	1.01	liter/kg
Sweeteners	Electricity	41,715	kWh/year	1.15e-01	kWh/kg
	Natural gas	1,262	m^3/year	3.66e-03	m^3/kg
	Refrigerant	3.95	kg/year	1.09e-05	kg/kg
	Water	**2.73e+05**	liter/year	0.750	liter/kg

Table A-9. Energy consumption per kilogram of commodities in the consumer phase across all food groups

Food Group	Passenger car distance traveled for shopping in km per kg	Home refrigeration in kWh per kg	Food preparation appliances in kWh per kg
Vegetables	0.179	0.552	1.312
Fruit and Juices	0.244	0.752	0.207
Milk and Dairy	0.239	0.736	0.482
Grains	0.192	-	1.556
Beef	0.434	1.335	1.391
Pork	0.277	0.853	0.889
Other meats	0.017	0.052	0.054
Poultry	0.326	1.005	2.521
Eggs	0.217	0.669	0.514
Fish and Seafood	1.196	3.683	1.882
Beans and Peas	0.264	-	18.42*
Nuts and Seeds	0.330	-	0.568
Fats and Oils	0.150	0.232	1.410
Sweeteners	0.139	-	0.485

* Electricity usage of coffee maker in household assigned to “beans/peas” group is a dominant factor.

Table A-10. Electricity consumption of food preparation appliances for each food group per household per year. The allocation was based on the consumption ratio of each food group.

Food Preparation	**kWh/year per household**	**Vegetables**	**Fruit and Juices**	**Milk and Dairy**	**Grains**	**Red Meat**	**Poultry**	**Eggs**	**Fish and Seafood**	**Beans and Peas**	**Nuts and Seeds**	**Fats and Oils**	**Sweeteners**
Blender	1	0.574	0.426										
Broiler	85					45.95	33.31		5.746				
Carving Knife	8	3.028	2.247			1.473	1.068		0.184				
Coffee Maker	140									140.0			
Deep Fryer	83	36.07				17.55	12.72		2.195			14.47	
Dishwasher	225	39.06	28.99	43.68	33.14	19.00	13.77	4.651	2.376	1.430	2.291	15.67	20.94
Egg Cooker	0.14							0.140					
Frying Pan	100	33.82				16.45	11.93	4.028	2.058			13.57	18.14
Hot Plate	90	15.62	11.60	17.47	13.26	7.600	5.510	1.860	0.951	0.572	0.916	6.268	8.377
Mixer	2		0.457	0.689	0.523								0.330
Microwave	280	55.79		62.40	47.34	27.14	19.68	6.644	3.395	2.043	3.272	22.39	29.91
Range with Oven	700	222.2			188.6	108.1	78.38		13.52			89.17	
Roaster	60					32.43	23.51		4.056				
Sandwich Grill	33			10.90	8.267	4.740	3.436	1.160	0.593			3.909	
Toaster	39				39.00								
Trash Compactor	50	8.679	6.442	9.706	7.364	4.222	3.061	1.033	0.528	0.318	0.509	3.482	4.654
Waffle Iron	20				20.00								
Waste Dispenser	7	1.215	0.902	1.359	1.031	0.591	0.429	0.145	0.074	0.044	0.071	0.488	0.652
Total	1,923	416	51.1	146	359	285	207	19.7	35.7	144	7.06	169	83.0

Table A-11. DALYs by major four diseases in U.S.

Cause of death or injury	DALYs	Lower bound	Upper bound
Oesophageal cancer	76,255	18,211	153,353
Stomach cancer	75,530	22,950	159,078
Liver cancer	4,249	1,581	8,492
Larynx cancer	6,372	-	16,182
Tracheal, bronchus, and lung cancer	377,589	130,054	735,769
Breast cancer	2,151	746	4,613
Uterine cancer	2,067	1,149	3,345
Colon and rectum cancer	**566,820**	**370,244**	**805,431**
Lip and oral cavity cancer	8,789	-	21,928
Nasopharynx cancer	1,929	-	4,731
Other pharynx cancer	5,178	-	13,358
Gallbladder and biliary tract cancer	427	206	767
Pancreatic cancer	1,910	572	4,137
Ovarian cancer	333	-	815
Kidney cancer	2,737	1,551	4,645
Thyroid cancer	460	190	874
Leukaemia	1,657	893	2,790
Rheumatic heart disease	5,849	1,340	15,793
Ischemic heart disease	**5,447,178**	**4,244,384**	**6,713,571**
Stroke	**1,038,098**	**750,190**	**1,384,865**
Hypertensive heart disease	146,737	43,606	370,651
Cardiomyopathy and myocarditis	34,561	8,838	85,391
Atrial fibrillation and flutter	42,782	10,933	108,390
Aortic aneurysm	12,776	3,236	31,720
Peripheral artery disease	6,364	1,405	18,017
Endocarditis	7,976	1,978	20,192
Other cardiovascular and circulatory diseases	65,197	17,424	149,860
Diabetes mellitus	**1,847,635**	**1,300,229**	**2,507,785**
Chronic kidney disease	147,063	52,485	313,153
Osteoarthritis	5,381	2,226	11,238
Low back and neck pain	10,437	5,632	18,770
Total	*9,952,487*	*6,992,252*	*13,689,704*

Table A-12. Relative contribution of environmental impacts associated with dietary choices.

		Fruit & Juices	Vegetables	Grains	Milk & Dairy	Eggs	Fish & Seafood	Nuts & Soy	Poultry	Beef	Pork	Other meats	Beans & Peas	Fats & Oils	Sweeteners
GWP	CCP	9.3%	11.5%	6.4%	15.5%	1.0%	2.9%	0.7%	4.7%	26.8%	9.9%	0.1%	1.5%	1.7%	4.1%
	CCP_S1	10.3%	12.7%	7.1%	17.2%	1.1%	3.2%	0.7%	5.2%	29.7%	0.0%	0.1%	1.7%	1.9%	4.5%
	CCP_S2	8.4%	10.4%	5.8%	14.0%	0.9%	2.6%	0.6%	4.2%	24.2%	18.5%	0.1%	1.4%	1.5%	3.7%
	CCP_S3	9.4%	11.6%	6.5%	15.7%	1.0%	2.9%	0.7%	2.6%	17.9%	20.0%	0.1%	1.5%	1.7%	4.1%
	RCP	15.1%	14.3%	4.9%	25.1%	0.8%	5.7%	0.7%	4.8%	15.7%	5.8%	0.1%	2.5%	2.1%	1.2%
	RCP_Veg	21.3%	20.1%	6.9%	35.4%	1.6%	0.0%	5.5%	0.0%	0.0%	0.0%	0.0%	3.5%	2.0%	1.7%
Water use	CCP	20.1%	7.2%	19.0%	5.6%	0.2%	0.6%	1.4%	6.3%	11.8%	9.4%	1.3%	0.3%	2.8%	6.6%
	CCP_S1	22.2%	8.0%	20.9%	6.2%	0.2%	0.7%	1.6%	7.0%	13.0%	0.0%	1.4%	0.3%	3.1%	7.3%
	CCP_S2	18.3%	6.6%	17.2%	5.1%	0.2%	0.5%	1.3%	5.8%	10.7%	17.7%	1.2%	0.3%	2.5%	6.0%
	CCP_S3	19.6%	7.0%	18.5%	5.5%	0.2%	0.6%	1.4%	3.4%	7.6%	18.3%	1.3%	0.3%	2.7%	6.4%
	RCP	34.2%	9.4%	15.1%	9.5%	0.2%	1.2%	1.4%	6.7%	7.2%	5.7%	0.8%	0.5%	3.5%	2.1%
	RCP_Veg	40.4%	11.1%	17.8%	11.2%	0.3%	0.0%	10.1%	0.0%	0.0%	0.0%	0.0%	0.6%	2.9%	2.5%
Land use	CCP	3.9%	3.9%	15.1%	12.3%	0.1%	1.3%	0.7%	4.1%	33.8%	9.0%	0.0%	0.7%	3.1%	7.4%
	CCP_S1	4.3%	4.2%	16.6%	13.5%	0.1%	1.4%	0.8%	4.5%	37.1%	0.0%	0.0%	0.8%	3.4%	8.1%
	CCP_S2	3.6%	3.5%	13.8%	11.2%	0.1%	1.2%	0.7%	3.7%	30.8%	17.0%	0.0%	0.7%	2.8%	6.7%
	CCP_S3	4.1%	4.0%	15.8%	12.8%	0.1%	1.4%	0.8%	2.4%	23.4%	18.7%	0.0%	0.8%	3.2%	7.7%
	RCP	7.6%	5.7%	13.7%	23.8%	0.1%	3.1%	0.9%	4.9%	23.6%	6.3%	0.0%	1.4%	4.5%	2.7%
	RCP_Veg	11.6%	8.8%	21.1%	36.5%	0.2%	0.0%	7.9%	0.0%	0.0%	0.0%	0.0%	2.2%	4.8%	4.1%

Table A.13. Footprints of each food group per kg, at consumer

.Impact category	IPCC GWP 100a	Non renewable, fossil	Land use	Water consumption
Unit	kg CO2 eq	MJ	m2a crop eq	m3
Fruit & Juices, at user	3.94	43.93	0.95	0.36
Vegetables, at user	4.94	53.12	0.95	0.13
Grains, at user	3.71	39.73	5.00	0.47
Milk & Dairy, at user	5.79	44.51	2.61	0.09
Eggs, at user	4.04	46.04	0.19	0.04
Fish & Seafood, at user	16.63	161.41	4.19	0.14
Nuts/Seeds/Soy, at user	7.24	97.40	4.75	0.67
Poultry, at user	10.82	94.69	5.42	0.63
Beef, at user	51.32	188.13	36.66	0.95
Pork, at user	27.66	201.63	14.26	1.11
Other meats, at user	42.22	504.43	0.06	6.61
Beans & Peas, at user	16.32	186.06	4.50	0.13
Fats & Oils, at user	7.44	47.10	7.75	0.52
Sweeteners, at user	4.06	35.23	2.74	0.32

6.2 Human Health Impacts

6.2.1 Non-Dietary Health Impacts

Figure 6.1 presents non-dietary human health impacts associated with air, water and land pollutant emissions of six distinct dietary scenarios in the unit of µDALY (disability-adjusted life year) per person per day. The IMPACT World+ damage assessment method was used for the analysis. Similar trends to GHGEs were observed. The pork-free meal (CCP_S1), replacing pork with the remaining food groups, decreased non-dietary human health impact from 55 to 51 µDALY. This result implies that removing pork from the diet might have positive effect on human health. Doubling daily consumption of pork by subtracting an equal number of added calories from the remaining food groups (CCP_S2) increased non-dietary human health impact to

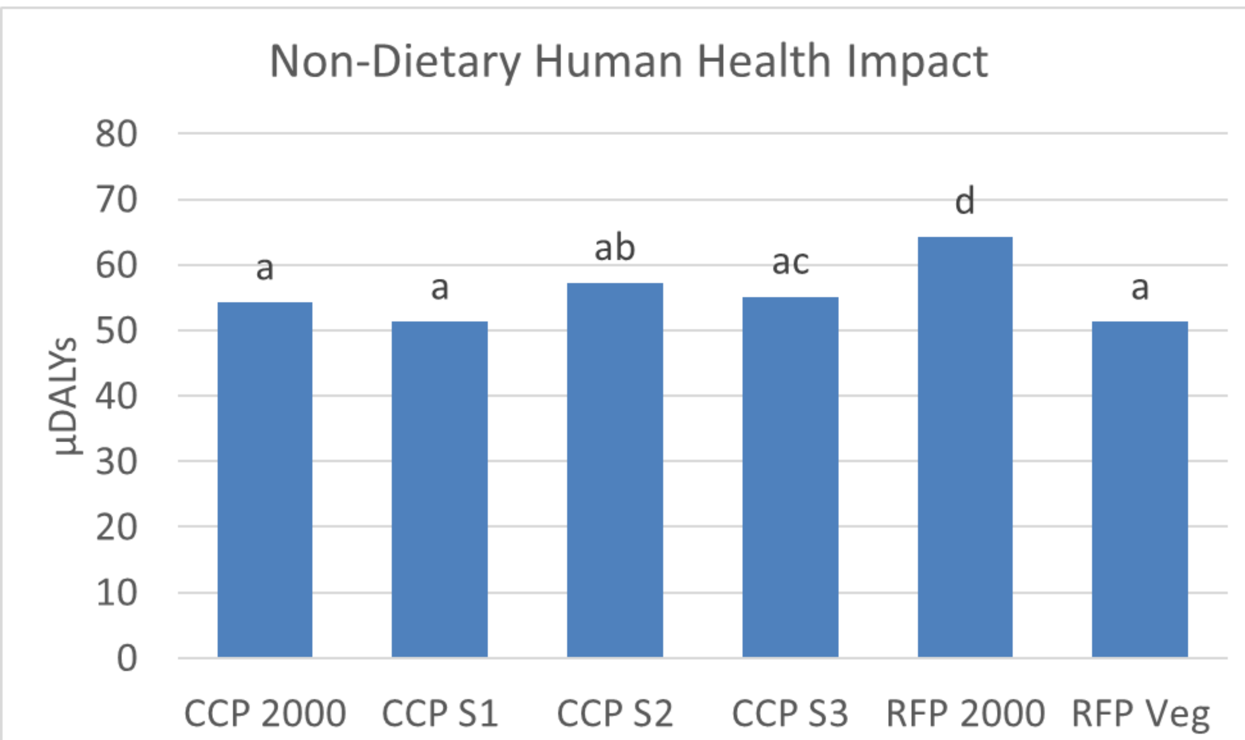

Figure 6.1. Non-dietary human health impact of six distinct dietary scenarios in µDALY per person per day. Columns with different letters are statistically different (p<0.01).

57 µDALY per person per day. The RCP scenario had the largest non-dietary human health impact as with as GHGEs. RCP_Veg diets display slightly decreased human health impact compared to CCP, equal to the pork-free scenario (CCP_S1). Competing effects associated with irrigation is the driver in non-dietary human health impact. Reduction of irrigation from reduction of red meat is more than offset by increased irrigation for substituting foods: fruits/juices, vegetables, milk/dairy, and nuts/seeds. Figure 6.2 shows the principal contributors to non-dietary related human health impacts. The main contributor was irrigation water use, which includes the processes, such as pumping and machinery activities, of water extraction from the environment.

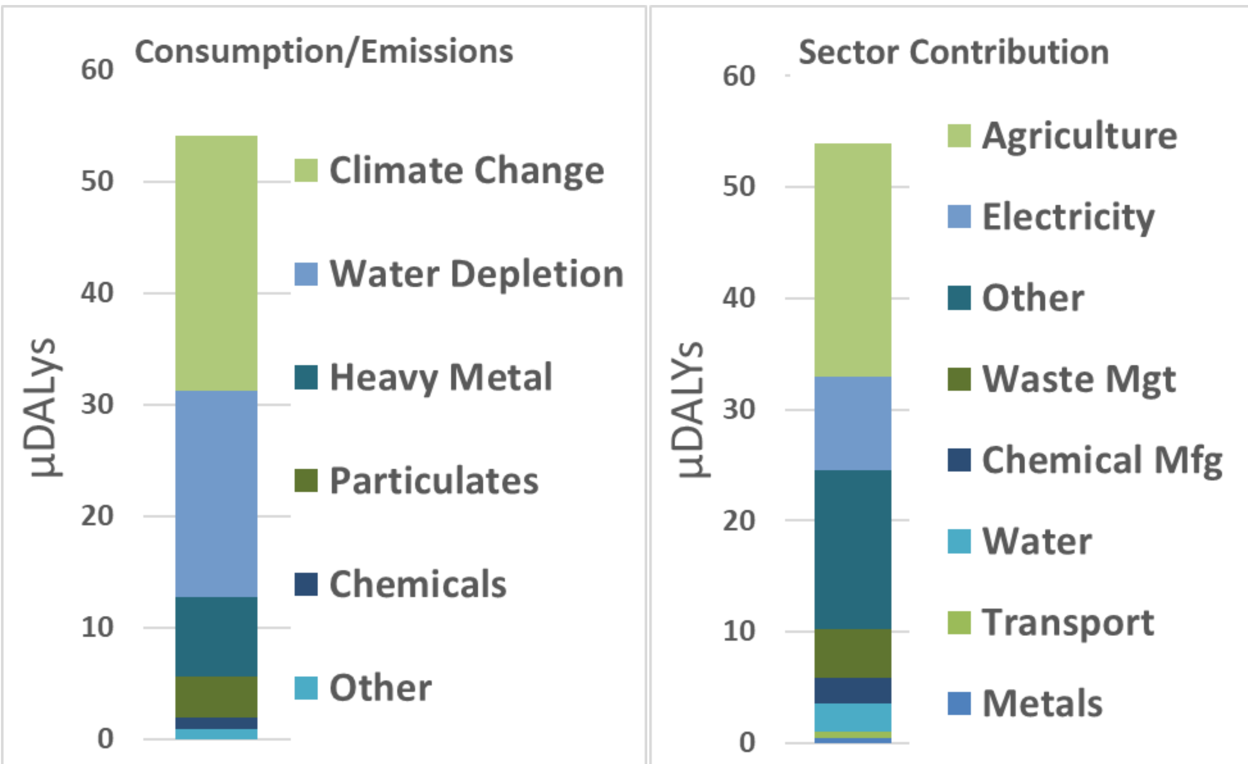

Figure 6.2. Substance consumption or emission (left) and sector (right) contribution to non-dietary related human health impact of the CCP scenario in µDALY per person per day.

Climate change effects on human health are associated with increased disease and illness. Secondary contributors were heavy metal emissions during fossil fuel burning to generate electricity. We performed a bootstrap statistical test using the Monte Carlo simulation data and found the RFP scenario has higher impacts than any of the others, which are all statisticaly the same except for the S2/S3 pair which are different. It is not clear what is driving this difference between S2/S3.

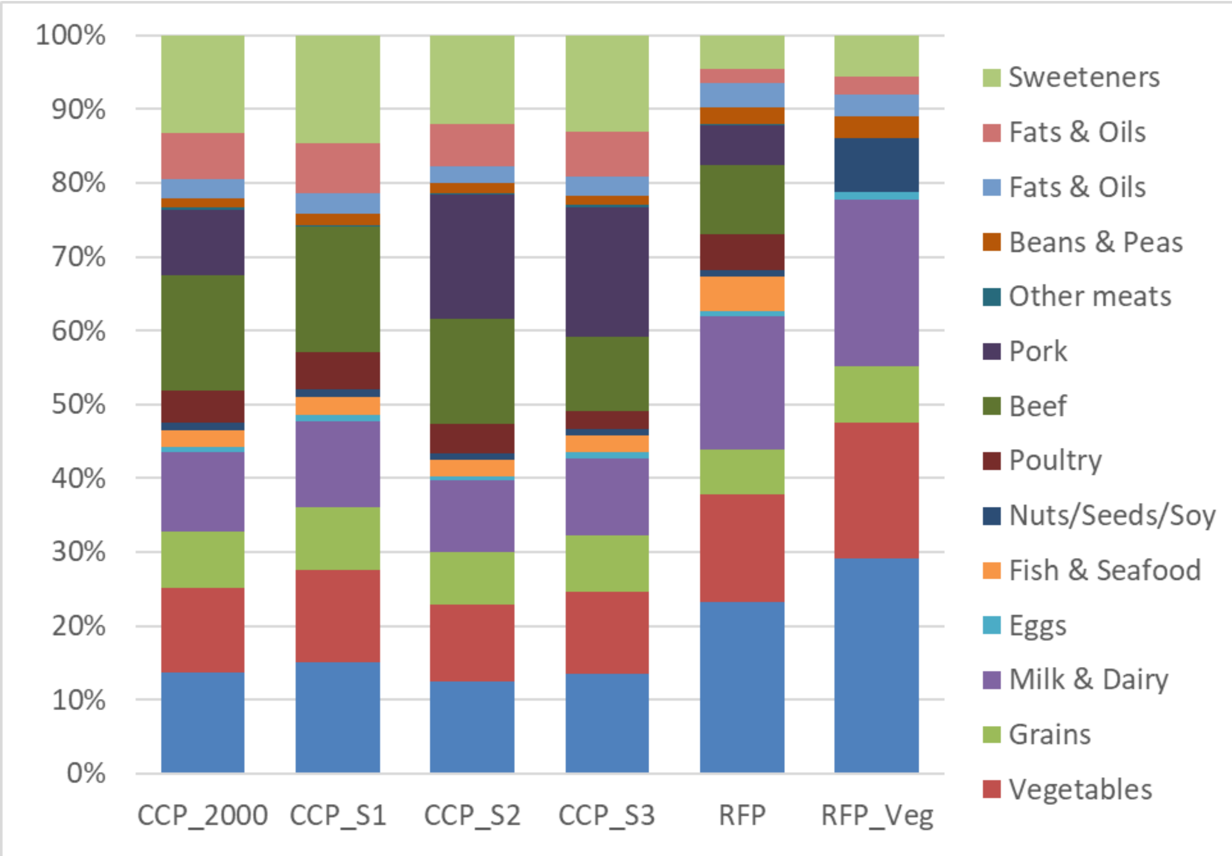

Figure 6.3. Relative contribution of each food group to non-dietary human health impact in percentage.

Figure 6.3 shows the relative contribution of each food group to non-dietary human health impact in percentage associated with each diet scenario. This chart is included to show an overall picture of how human health impact varies with dietary changes. It is obvious that the recommended increased intake of fruits/juices, vegetables, milk/diary, and nuts/seeds/soy in the vegetarian diet are dominant contributors affecting the increase of non-dietary human health impact This result indicates that removing pork from the meal has minor or insignificant beneficial effect on human health.

6.2.2 Dietary Human Health Impact

Figure 6.4 presents the dietary human health impact of five dietary scenarios relative to the CCP_2550 baseline scenario in µDALY (disability-adjusted life year) per person per day. As we mentioned in Section 2.2.1, we analyzed the impacts of dietary choices on human health by using a risk assessment framework with four disease states (coronary heart disease (CHD), diabetes, stroke, and colorectal cancer). As shown in the CCP_S1 bar, moving to diets without pork would

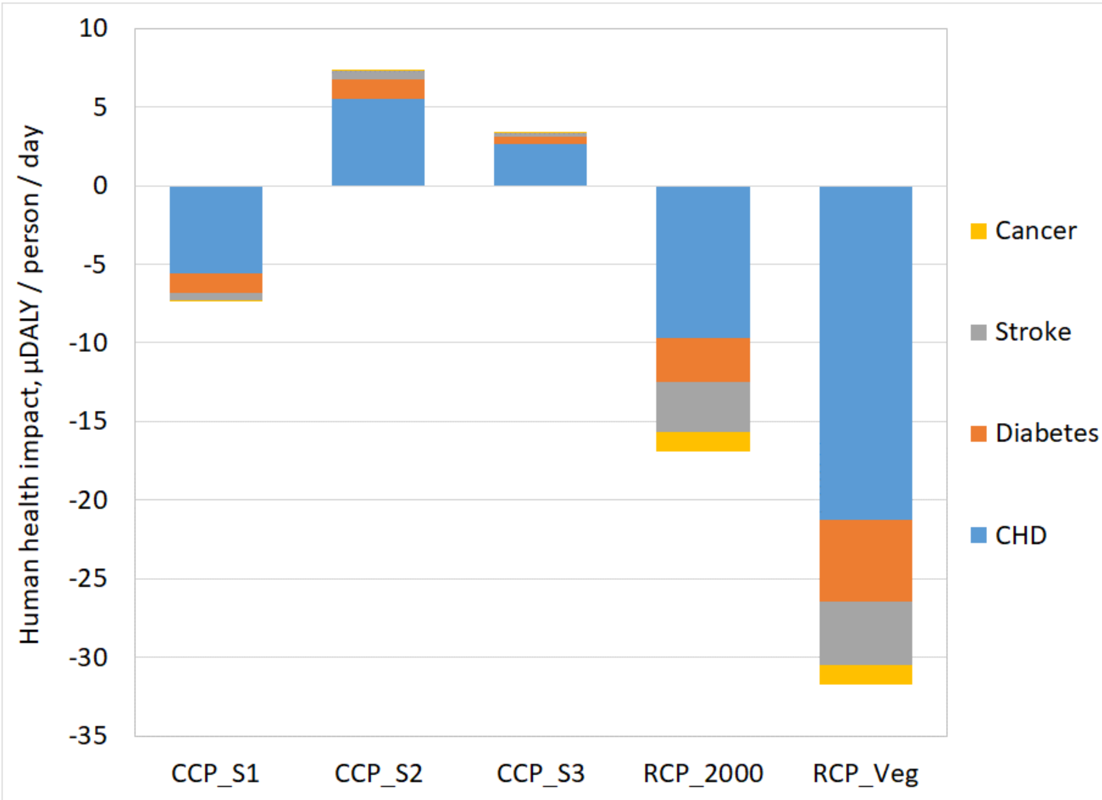

Figure 6.4. Dietary related human health impact of five distinct dietary scenarios relative to baseline scenario (CCP) in µDALY per person per day.

have health benefits – it should be noted that the dietary health risk data do not differentiate types of meat other than processed meats. Compared with the reference scenario, we project that pork-free diet (CCP_S1) would result in 7.4 avoided µDALY per person adopting the diet per day. By adopting the USDA recommended diet, the health benefit increases to 16.9 avoided µDALY per person adopting the diet per day. The health benefit further increased with the recommended vegetarian diet. The dietary human health estimates of decreasing red meat intake were in general agreement with current available epidemiological studies of dietary choices. Le and Sabaté (2014) reported that the mortality in vegetarians was lower of 12-20% compared with non-vegetarians in the U.S. Tilman and Clark (2014) and Orlich et al. (2014) also reported similar results by using a meta-analysis and a cohort study, respectively. According to the result, CHD impact contributes the largest to dietary human health in DALYs followed by diabetes, stroke, and cancer.

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