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Sustainability and Health Impacts of Pulse Crops in the United States using Life Cycle Assessment

Prathamesh A. Bandekar
University of Arkansas, Fayetteville

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Sustainability and Health Impacts of Pulse Crops in the United States Using Life Cycle Assessment

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by

Prathamesh A. Bandekar
Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth
Bachelor of Technology in Agricultural Engineering, 2006
University of Arkansas
Bachelor of Science in Biological Engineering, 2015

December 2022
University of Arkansas

This dissertation is approved for recommendation to the Graduate Council.

Marty D. Matlock, Ph.D.
Dissertation Director

Greg Thoma, Ph.D.
Committee Member

Yi Liang, Ph.D.
Committee Member

Perry Miller, Ph.D.
Committee Member

Abstract

Environmental sustainability and human health impact of pulses produced and consumed in the United States was assessed using life cycle assessment (LCA). The study included three objectives 1) to estimate environmental impact of current production and consumption practices in the United States using attributional LCA; 2) to estimate environmental and human health impact of iso-caloric diets containing varying amounts of pulses using Hybrid-LCA and Combined Nutritional and Environmental-LCA (CONE-LCA); and 3) to estimate environmental impact of increased demand for pulses using consequential LCA. Scope of the study varied for each objective with system boundary encompassing cradle-to-grave activities for objective 1 and 2 and cradle-to-processor gate activities for objective 3.

In objective 1 cradle-to-grave environmental impacts of current production practices in the US were estimated for dry bean, chickpea, field pea, and lentil for the functional unit (FU) of 60 g of pulses (approx. ¼ cup) consumed per week. In addition, impact of four cooking methods, open-vessel cooking (OVC), cooking in stovetop pressure cooker (SPC), cooking in electric pressure cooker (EPC), and cooking in larger quantity (e.g., 1 kg instead of 60 g) in open vessel (OVC-RF1), was evaluated. Statistically significant decrease in environmental impact (all impact categories except LU and WC) for all species of pulses was achieved with EPC and OVC-RF1 compared to OVC. Energy used for cooking at the consumer stage, and resource use (fertilizers, fossil fuels etc.) were identified as the hotspots in the study.

Comparison of current (CDP) and recommended (RDP) iso-caloric diets containing varying quantities of pulses was conducted in Objective 2 for FU of 1800 kcal to females and 2400 kcal to males. RDPs included healthy-styled US diet (HealthyUS), ovo-lacto-vegetarian diets according to 2015 (Veg2015) and 2010 (Veg2010) USDA recommendations, and vegan

diet (Vegan2010) according to 2010 USDA recommendations. Compared to CDP, statistically significant increase in GWP was observed for HealthyUS for sex-specific diets, while Vegan2010 lowered (statistically significant) GWP for both sexes. Statistically significant health benefits were offered only by Vegan 2010, Veg2010, and Veg2015. Pulses provided 29% to 42% of protein in vegetarian and vegan diets while contributing only between 0.06% and 0.84% of GWP for these diets. Moreover, when compared to other sources of protein pulses had the lowest GWP and greatest nutritional density.

Pulses also offered potential environmental gains compared to beef even when production and processing of pulses was increased to meet potential increase in demand. The FU for Objective 3 was an amino acid profile comparable to beef. Beef was considered as the protein source substituted by pulses because of its high environmental and adverse health impact. To meet the requirements of the FU consumption of pulses was complemented with rice at a ratio of 1.35:1 (pulses+rice). While this additional production and processing of pulses and rice would increase the environmental impact, potential environmental gains could be achieved if increased demand for protein were to be fulfilled by pulses and rice instead of beef (i.e., 57 – 92%).

The study concluded that pulses can be environmentally sustainable source of protein especially if they are cooked in electric pressure cooker and/or in batches larger than 60 g. Considering their higher nutritional density score and lower environmental impact compared to other sources of protein, their increased inclusion in diet could offer health benefits by lowering disability adjusted life years (DALYs) associated with CDP. While this increased inclusion of pulses may require increasing their production and processing, net environmental benefits can still be achieved compared to complete reliance on animal sourced protein such as beef. However, complete substitution of animal-sourced protein with only pulses is not recommended because such change may cause unintended consequences in terms of meeting nutritional requirements. Care must be taken to ensure that all nutritional requirements are fulfilled while decreasing environmental impacts.

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Chapter 1 Introduction

1.1 Background

Global human population is expected to reach 9.2 billion by 2050 requiring 60 to 70 % increase in the agricultural production and possibly expansion of global arable land (Silva, 2018). Growing global population is also expected to increase competition for fresh water, land, and energy. Moreover, imminent climate change is expected to exacerbate pervasive issues in agriculture such as poor soil quality, soil erosion, water stress, crop loss due to pests, and growing competition for available resources. This has increased the pressure on agriculture to improve production efficiency and sustainability. Globally, the food sector contributes 19 to 29% of greenhouse gas (GHG) emissions with majority of CH_4 and N_2O emissions originating from agriculture (MacWilliam et al., 2018). Globally agriculture depends on only three row crops, corn, rice, and wheat, which occupy 40% of global arable land to fulfill 50% of global caloric demand (Ebert, 2014). These crops require substantial amount of synthetic nitrogen (N) fertilizers, which contribute to GHG emissions and consequently to the climate change (MacWilliam et al., 2018). Possible expansion of arable land, especially if it causes deforestation, and intensification necessitated by growing population and climate change may cause a positive feedback loop expediting the climate change and aggravating its impacts. Moreover, reliance on few crops to satisfy the demand of growing population might be economically, environmentally, and agronomically perilous. Therefore, diversification in agriculture is necessary to improve sustainability of the sector while simultaneously meet increasing demand for food. This will also help in breaking cereal crops pest cycle, a well-known limitation of monoculture.

In addition to breaking cereal crop disease cycles, pulse crops can help in lowering nutritional dependency on major commodity crops and reduce the use of N fertilizer in crop production. Pulses, leguminous crops harvested for edible dry seeds, include species such as dry bean (*Phaseolus vulgaris*), chickpea (*Cicer arietinum*), field pea (also known as dry pea) (*Pisum sativum*), and lentil (*Lens culinaris*). The N fixing ability of pulses greatly lowers their demand for inorganic N fertilizers, which ranges between 11 and 56 kg N ha^{-1} (Brouwer et al., 2015; Franzen, 1998; Kandel et al., 2018; Schatz and Endres, 2009). However, chickpea, field pea, and lentil can also be grown without any N fertilizers. Comparatively N demand for corn ranges from 110 to 280 kg N ha^{-1} (Halvorson and Bartolo, 2014; Kim et al., 2009; Kim and Dale, 2008). Besides lowering their own demand for synthetic N fertilizers, when included in rotation, pulses also improve yield and protein content of following cereal crops (Burgess et al., 2012; Campbell et al., 1992; Zentner et al., 2001). This could potentially lower the use of N fertilizer in agriculture, which is known to be responsible for GHG emissions,

The demand for protein is also expected to increase in the future both as a result of increasing population and improving socio-economic factors such as income (Henchion et al., 2017). This is also expected to double the demand for animal-sourced protein by 2050, which has been responsible for 30% of human-induced global biodiversity loss (Westhoek et al., 2011). Growing animal-sourced food is also inefficient in terms of resource use with only 30% of feed converted to meat and milk fit for human consumption (Westhoek et al., 2011). Besides, animal-sourced protein such as red meat has been linked with elevated risk of type 2 diabetes, heart disease, and stroke, and colorectal cancer (Feskens et al., 2013; Key et al., 2019; Micha et al., 2017b, 2017a; Yang et al., 2016; Yip et al., 2018). This increasing demand for protein could be fulfilled by pulses, which contain 18 to 36% of protein (FAO, 2016) and are considered healthier source of protein (Röös et al., 2020). Pulses have a potential to improve nutritional quality of a diet while simultaneously decreasing GHG emissions as reported by Chaudhary et al. (2018). Pulses are rich in dietary fiber, protein, folate, zinc, iron, and magnesium and low in saturated and total fats (Mitchell et al., 2009). Moreover, increased consumption of pulses has been shown to offer protection against coronary heart diseases (Afshin et al., 2014; Bechthold et al., 2019; Viguiliouk et al., 2019). Thus, both environmental and health gains could be achieved by increasing the consumption of pulses in human diet

1.2 Research problem

Pulses show a potential to offer environmental and health benefits. However, it is important to quantify any potential benefits and risks associated with any changes to existing system and with increased production of pulses in the United States. Life cycle assessment (LCA) can be a valuable modeling framework for such evaluations. LCA is a measurable and quantifiable tool that could be valuable to measure environmental impacts of existing product systems, identify hotspots, determine potential for improvements, and assess applicability of alternative production systems (ISO, 2006). It can be beneficial for researchers, growers, and policy makers to make informed decisions.

LCA studies measuring environmental impacts associated with production of pulses exist in Canada and few other parts of the world (Kulshreshtha et al., 2013; MacWilliam et al., 2015, 2014; Nemecek et al., 2008; Tidåker et al., 2021). However, until the publication of study included as Chapter 2 in this dissertation, only one other study conducted by Gustafson (2017) existed for the US, which accounted for 11% of global exports of pulses (Bond, 2019). Gustafson (2017) used survey data collected in six states (Idaho, Michigan, Minnesota, Montana, Washington, Wisconsin) and covering five pulse crops (chickpeas, dark red kidney beans, dry peas, lentils, navy beans). However, the survey did not include North Dakota, one of the largest producers of pulses in the US (USDA National Agricultural Statistics Services, 2017). Gustafson (2017) reported environmental impact only for global warming potential (GWP) and water consumption and these impacts were aggregated for all pulse crops included in the study. Moreover, the study only considered farmgate activities limiting the system boundary to cradle-to-farmgate. While assessment of cradle-to-farmgate impacts is important in agricultural LCAs, considering post-farmgate activities is essential to provide holistic sustainability assessment. It would provide an opportunity to identify hotspots in the product chain where efforts and resources can be diverted to improve product sustainability.

Similarly, health impacts of pulses have been studied in terms of protection they offer against coronary heart disease as mentioned in section 1.1. However, LCA studies measured their contribution to impact of healthier diets only in terms of environmental impact (known as midpoint impact in LCA) categories (Kim et al., 2020; Pathak et al., 2010; Veeramani et al., 2017). Kim et al. (2020) included dry beans and dry peas in the study that compared current and recommended dietary patterns in the United States, but the focus of the study was primarily on dietary patterns as a whole and only in terms of midpoint impacts. Environmental impacts often affect human health through pathways elaborated by Huijbregts et al. (2017). For example, GHG and particulate matter emissions can be detrimental to human health and can offset any health benefits offered by diets of high nutritional value (Vieux et al., 2013). Therefore, a true impact of food system and consequently of pulses can only be measured by evaluating their impact on human health measured by endpoint impact categories in LCA. Emission-related endpoint impact on human health is measured in terms of disability adjusted life years (DALYs) in LCA (Huijbregts et al., 2017), which can be combined with consumption-related health impact of dietary groups (Stylianou et al., 2021) to estimate net human health impact of diets in general and of pulses in particular. Such studies exploring endpoint impacts for diets with focus on pulses are, to the best of our knowledge, non-existent for the United States.

If production of pulses needs to increase to meet the demand of growing population for protein, it is important to evaluate resulting changes to the current environmental impacts of food systems. This is primarily because increased agricultural production can be achieved only through expansion of arable land or intensification of current production system (Schmidt, 2008). Either pathway would change overall environmental impact due to land use change or increased use of resources such as fertilizers, pesticides, fossil fuels, etc. These changes can be estimated using consequential LCA, which is considered prospective LCA compared to retrospective attributional LCA often used for estimating impact of current product system (European Commission. Joint Research Centre. Institute for Environment and Sustainability., 2010). Consequential LCA has been used by researchers to measure impacts on agricultural systems associated with increased demand for biofuels (Kløverpris and Mueller, 2013; Parajuli et al., 2018, 2017; Searchinger et al., 2008; Tonini et al., 2012), dairy milk (Thomassen et al., 2008), and wine (Larrea-Gallegos et al., 2019). However, changes to environmental impact from increased production of pulses in the United States have not been studied.

This dissertation aspires to begin filling this existing gap in scientific knowledge regarding environmental sustainability and human health impacts of pulses produced in the United States. It was planned to achieve this goal through systematic examination of current pulse production system to benchmark their environmental sustainability, identify hotspots in the pulse product chain, transform environmental impacts into impact on human health, and estimate impacts associated with increased consumption. The work carried out in this dissertation contributed to the scientific knowledge necessary for planning sustainable and prosperous future for the humanity.

1.3 Objectives

An overarching goal of this exploratory research study was to evaluate sustainability and human health impacts of pulse crops in the United States. An effective modeling framework of LCA was deployed to achieve this goal by using three different methodological paradigms, i.e., attributional LCA, hybrid input-output and process LCA, and consequential LCA. The specific objectives addressed in the dissertation are:

Objective 1- to estimate environmental impact of cradle-to-grave activities involved in production and consumption of pulses using attributional life cycle assessment.

Objective 2- to evaluate human health impact of current and recommended dietary patterns with varying quantities of pulses, with specific focus on contribution of pulses

Objective 3- to estimate environmental impact associated with increased demand for pulses in the United States

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Chapter 2 Cradle-to-grave life cycle assessment of production and consumption of pulses in the United States

Prathamesh A. Bandekar, Ben Putman, Greg Thoma, Marty Matlock

Abstract

Environmental impact associated with production and consumption of pulses in the United States was evaluated using life cycle assessment (LCA). The system boundary was set to cradle-to-grave with a functional unit of 60 g (approx. ¼ cup dry pulses) of pulses consumed in a US household. Pulse crop species modeled in the study included field pea (*Pisum sativum*), lentil (*Lens culinaris*), chickpea (*Cicer arietinum*), and dry bean (*Phaseolus vulgaris*). Three methods of cooking pulses at the consumer stage tested in the study were cooking in open vessel on electric cooking range (OVC), cooking in stovetop pressure cooker on electric cooking range (SPC), and cooking in electric pressure cooker (EPC). OVC formed the base scenario against which all other scenarios were compared. The environmental impact of pulses varied with type of pulse crop, cooking method, and the batch size. Consumption of approximately 60 g of dry pulses resulted in the greatest environmental impact for OVC. The consumer stage contributed at least 83, 81, 76, 75, and 87% for global warming potential (GWP), fossil resource scarcity (FRS), water consumption (WC), freshwater eutrophication (FE), and marine eutrophication (ME), respectively for this scenario. EPC resulted in the lowest in the environmental impact, compared to OVC, for GWP, fossil resource scarcity, FE, and ME for all pulse species, which was validated in the uncertainty analysis. SPC, on the other hand, decreased the impact across these categories only for chickpea and dry bean. The uncertainty analysis suggested that the differences associated with cooking methods in the mean land use and water consumption scores of pulses were statistically non-significant. The impact categories were also highly sensitive to

the mass of pulses cooked in a batch. Increasing the reference flow in OVC to 1 kg decreased the environmental impact of pulses by 49 to 87% for all impact categories, excluding land use. Overall, the study identified the consumer stage as the hotspot for environmental impact in the supply chain of pulses in the United States. The large contribution of the consumer stage to the overall environmental impact of pulses was attributed to electricity consumption for cooking and associated upstream emissions.

2.1 Introduction

Growing population, dwindling resources, and changing climate have increased the pressure on agriculture to improve production and efficiency while maintaining or improving sustainability of the sector. The food sector contributes 19 to 29% of global anthropogenic greenhouse gas (GHG) emissions and agriculture is the largest contributor of CH_4 and N_2O emissions (MacWilliam et al., 2018). A few major grain crops such as corn, rice, and wheat cover approximately 40% of global arable land and satisfy 50% of caloric demand of global population (Ebert, 2014). Reliance on few major crops to meet the demands of growing population could be agronomically, environmentally, and economically perilous. These crops require substantial amount of synthetic nitrogen (N) fertilizers which results in increased GHG emissions from agriculture (MacWilliam et al., 2018). Monoculture also increases pesticide demand of the sector and results in pest-accumulation due to lack of crop diversity (MacWilliam et al., 2015). Therefore, diversification in crop production is important to improve pest and nutrient management, food production, and overall sustainability of the agriculture sector.

Pulses, which include dry edible leguminous crops such as dry beans, field peas, chickpeas, and lentils, when included in crop rotation, can play a major role in achieving these objectives by breaking disease and insect cycles and improving soil fertility (MacWilliam et al., 2015). Pulses have an ability to fix atmospheric nitrogen to meet most of their nitrogen demand. The synthetic N fertilizer demand of pulses ranges between 0 and 56 kg N/ha (Brouwer et al., 2015; Franzen, 1998; Kandel et al., 2018; Schatz and Endres, 2009) while that of corn ranges between 110 and 280 kg N/ha (Halvorson and Bartoli, 2014; Kim et al., 2009; Kim and Dale, 2008). This reduced reliance of pulses on synthetic N fertilizer offer various environmental and agronomic benefits. The production of synthetic N fertilizers is energy intensive and their application to soil results in GHG emissions, marine eutrophication, and atmospheric acidification. These impacts can be mitigated by including pulses in crop rotation, which also benefits following cereal crop in terms of improved yield and protein content (Burgess et al., 2012; Campbell et al., 1992; Miller et al., 2018; Walley et al., 2007; Zentner et al., 2001).

Pulses can be an excellent source of protein in human diets. Pulses contain 18 to 36% protein and are rich in nutrients, vitamins, and minerals (FAO, 2016). Furthermore, high levels of complex carbohydrates and fiber can help stabilizing blood sugar levels, while also providing a feeling of satiety. Chaudhary et al. (2018) reported that when refined wheat flour in pan bread, breakfast cereal, and pasta was partially replaced by yellow pea flour, the nutrient balance score of these products improved by 11, 70, 18% and decreased GHG emission by 4, 11, and 13%, respectively. Consuming pulses such as dry beans and peas was found to increase fiber, protein, folate, zinc, iron, and magnesium intake in human diet while reducing intake of saturated fat and total fat (Hall et al., 2017; Grusak, 2009; Mitchell et al., 2009; Wood and Grusak, 2007).

However, evaluation of potential benefits and risks associated with any changes made to the existing cropping system is important before these changes are incorporated. Life cycle assessment (LCA), a measurable and quantifiable framework for such assessment, can be valuable for researchers, growers, and policy makers in making informed decisions (ISO, 2006a).

While LCA studies of pulse production are available for Canada and a few other parts of the world (Kulshreshtha et al., 2013; MacWilliam et al., 2014a, 2015; Nemecek et al., 2008; Tidåker et al., 2021), only one study exists specific to the USA, which accounted for 11% of global pulse exports in 2017 (Bond, 2019). Gustafson (2017) reported an LCA of US pulse production using survey data collected in six states (Idaho, Michigan, Minnesota, Montana, Washington, Wisconsin) and covering five pulse crops (chickpeas, dark red kidney beans, dry peas, lentils, navy beans). The study estimated that GHG emissions associated with pulse crop production were 0.26 and 0.31 kg CO_2e/kg for non-irrigated and irrigated crops, respectively. The irrigation water use was 0.19 m^3/kg, lower than many other row crops. However, this study did not follow many of the commonly used and internationally standardized methods for performing life cycle assessment and included only two impact categories. The results for these two impact categories were aggregated for all types of pulse crops and differentiated only between irrigated and non-irrigated crops. Also, the underlying survey data excluded North Dakota, the second largest pulse production states in the United States (USDA National Agricultural Statistics Services, 2017). Furthermore, the study was ‘cradle to farmgate’ and did not consider post-farmgate processes, which is necessary to provide a holistic sustainability picture of pulse crops. Assessment of impacts associated with both ‘cradle to farmgate’ and ‘post-farmgate’ supply chains, including consumption stage, could be important in evaluating and improving sustainability of agricultural sector in general and of pulse production sector specifically. The objective of this study was to perform a ‘cradle to grave’ attributional LCA of pulse crop production in the US using national average production and consumption practices for the most commonly grown pulses: pea, lentil, chickpea, and dry bean.

2.2 Material and methods

Production and consumption of pulses was modeled in OpenLCA (GreenDelta). The background processes involved in production, processing, retail, and cooking of pulses were modeled using ‘EcoInvent 3.4 – allocation, cut-off by classification’ database (Wernet et al., 2016). The model was divided into four stages: crop production, processing, retail, and consumer stage. Process boundaries for each stage encompassed gate-to-gate activities, except for crop production. For example, the processing stage included all activities from transportation of harvested pulses to the processing facility to loading packaged pulses into tractor-trailer containers for distribution to retail. On the other hand, the boundary for crop production stage was set to cradle-to-farmgate.

2.2.1 Goal and Scope of Study

The primary goal of this study was to evaluate impacts associated with production and consumption of pulses in the United States using attributional LCA. The impacts of pulses were evaluated in terms of global warming potential (GWP) estimated over 100-year horizon, fossil resource scarcity (FRS), land use (LU), water consumption (WC), freshwater eutrophication (FE), and marine eutrophication (ME), using ReCiPe 2016 (H) midpoint life cycle impact assessment (LCIA) method (Huijbregts et al., 2017). These impact categories characterized sustainability of pulse supply chain in the United States.

2.2.1.1 Functional Unit

The functional unit (FU) quantifies the product studied and defines the reference flows for all the inputs and outputs. A functional unit of 60 g of pulses, cooked and consumed in the US household, was selected for this study. The functional unit represented current average weekly consumption of pulses in the United States (HHS and USDA, 2015). The cooking methods evaluated in the study include boiling or pressure-cooking pulses in water until they are cooked. Generally, cooked pulses are used as an ingredient in recipes such as soups, salads, spreads or can be consumed with rice. However, formulating and evaluating these recipes was out of scope for this study.

2.2.1.2 System Boundary

Defining system boundary is crucial in LCA (ISO, 2006a). The system boundary determines the processes in the product life cycle that are included or excluded from analysis. The system boundary for this study was cradle (production of seeds and other agronomic inputs and crop production) to grave (consumption of pulses at consumer's home). The processes included in the system boundary are illustrated in Figure 2.1. Resource use and wastage at each stage were fully accounted for each process. Consumption of pulses away from home was excluded from the study. The system boundary also excluded processing and consumption of various finished products (hummus, canned beans, soups etc.) containing pulses. The consumer stage of the analysis was restricted to purchase, cooking, and consumption of dry pulses only. A

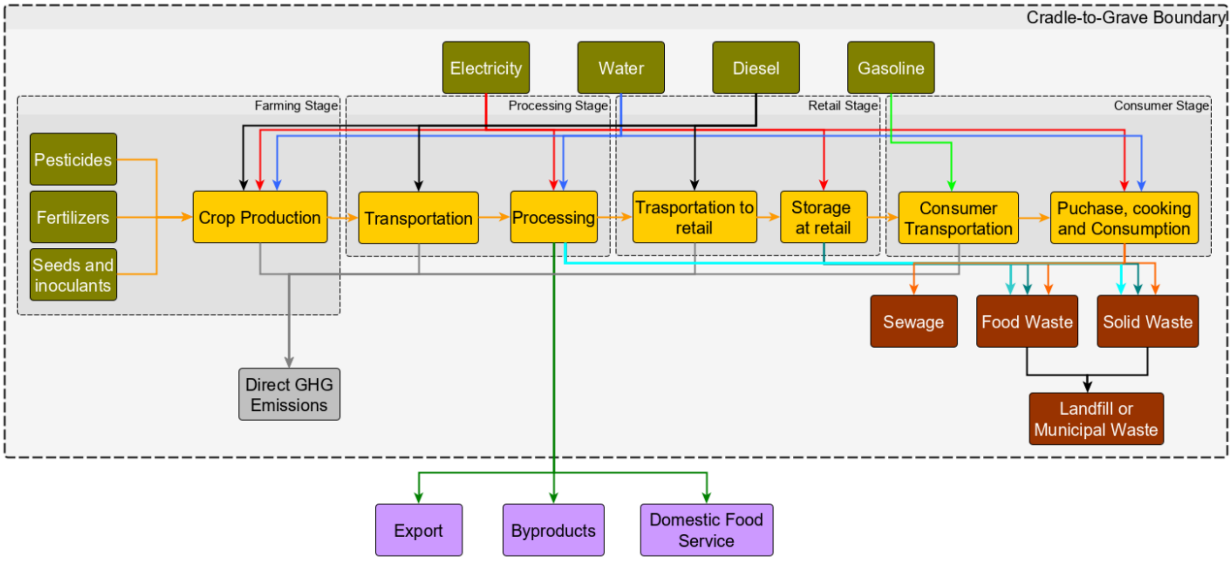


Figure 2.1- Conceptual model with system boundaries and processes in production and consumption of pulses in the United States.

cutoff criterion of 1% was established for mass flows and/or environmental impact categories. However, data were included regardless of cutoff criterion if they were readily available.

2.2.1.3 Allocation Methodology

Allocation of resources and burden is required for a process with multiple outputs. An ISO 14044 allocation hierarchy (ISO, 2006b) was followed in this study for allocation of inputs and emissions. The primary byproduct of harvesting at the farming stage is crop residue, which is often left on the soil (USA Dry Pea & Lentil Council, 2019). Although the crop residue may provide nutrients to the crops planted in the following season (Bedard-Haughn et al., 2013; Miller et al., 2015), the system boundary excluded recycling of soil nutrients and the burden of material, resources, and emissions was allocated to the harvested pulses. A single processing plant often processes several crops. Therefore, the system specific to the pulses was separated from processing of other crops at the processing facility. Processing pulses primarily produces seed coat and sometimes broken and powdered pulses. Due to lack of data regarding fate of these materials, they were treated as waste disposed in the municipal landfill. Therefore, inputs and emissions were allocated to the packaged pulses. For multifunctional activities such as retail allocation based on shelf space occupied was adopted. A revenue-based approach was adopted at the consumer stage to attribute transportation associated with grocery purchase as well as refrigeration load and microwave usage to pulses when necessary.

2.2.2 Life cycle inventory

Data for life cycle inventory (LCI) was obtained from peer-reviewed manuscripts, crop budgets, extension documents published by the universities, technical specifications published by the manufacturers of crop processing machineries, and various publicly available data repositories and sources. We also consulted experts from the universities and the United States

Department of Agriculture (USDA) for crop production data such as seeding rate, fertilizer application rates, and tillage practices.

2.2.2.1 Cradle-to-farmgate

Cradle-to-farmgate activities constitute the first stage in the cradle-to-grave system boundary. It includes seed production and transport, production and transport of fertilizers and pesticides, and all other on-farm activities associated with production of pulses.

2.2.2.1(a)Crop production

The pulse production methods and related data were obtained from expert opinion and from crop budgets and published extension documents. Crop yield was obtained from USDA-NASS survey data. Based on expert opinion, lentils, field peas (also known as dry peas), and chickpeas were modeled as no-till, dry land crops. This represented the general pulse production practices in Montana and North Dakota, the two largest pulse producing states in the USA. Production practices could vary in other pulse production states. However, no state-specific data were available. Moreover, in 2018 Montana and North Dakota together produced 86 and 81% of total national production of field pea and lentil, respectively (USDA National Agricultural Statistics Services, 2017). Therefore, the production practices in these two states were assumed to represent national average. Data provided by experts included fertilizer application rates, seeding rates, and information about types of chemicals used (Miller et al., Personal Communication). Fertilizer application rates suggested by the experts were similar to those used by MacWilliam et al. (2014) for dry pea and lentil production. The dry bean production practices varied from other pulse crops (Miller et al., Personal Communication). However, in absence of specific data, the dry bean production was modeled as a conventionally tilled, dryland crop (Brouwer et al., 2015). Fertilizer application rates for dry beans were considered as an average of the upper and lower threshold provided by Brouwer et al. (2015). Production data for pulse production is provided in Table 2.1.

Table 2.1- Life cycle inventory for cradle-to-retail stage for variety of pulses. Data in the table are presented for the reference flow of each stage

Parameter	Chickpea	Dry bean	Field pea	Lentil
Farming stage[e]				
Seeding rate, kg/ha	179.33	146.83	168.13	56.04
Yield, kg/ha (Reference flow)	1769.83	1922.60	2028.45	1342.20
Nitrogen fertilizer, kg N/ha	5.60	44.83	5.60	5.60
Phosphorous fertilizer, kg P_2O_5/ha	28.02	33.63	28.02	28.02
Potassium fertilizer, kg K_2O/ha	8.41	8.41	8.41	8.41
Pendimethalin, kg a.i./ha	1.24	-	1.24	1.24
Metolachlor, kg a.i./ha	1.60	-	1.60	1.60
Paraquat, kg a.i./ha	0.54	0.54	0.54	0.54
Glyphosate[d], kg a.i./ha	-	1.68	-	-
Dimethenamid, kg a.i./ha	-	0.86	-	-
Picoxystrobin[f], kg a.i./ha	0.66	-	-	-
Processing stage				
Reference flow, kg	1.00	1.00	1.00	1.00
De-stoning electricity [a], kWh	4.46 E-04	4.46 E-04	4.46 E-04	4.46 E-04
Grading, electricity [b], kWh	3.34 E-05	3.34 E-05	3.34 E-05	3.34 E-05
Decorticating, electricity [b], kWh	1.25 E-05	1.25 E-05	1.25 E-05	1.25 E-05
Optical sorting, electricity [b], kWh	1.79 E-04	1.79 E-04	1.79 E-04	1.79 E-04
Splitting, electricity [b,c], kWh	1.25 E-03	1.25 E-03	1.25 E-03	1.25 E-03
LDPE film, kg	6.06 E-03	6.06 E-03	6.06 E-03	6.06 E-03
Water, kg	0.13	-	0.13	-
Transportation, tkm	0.152	0.152	0.152	0.152
Pulses hauled from the farm, kg	1.52	1.52	1.52	1.52
Pulses processed after de-stoning, kg	1.33	1.33	1.33	1.33
Retail Stage				
Pulses, reference flow, kg	1.00	1.00	1.00	1.00
Electricity, kWh	0.02	0.02	0.02	0.02
Transportation, tkm	0.48	0.48	0.48	0.48
Packaged pulses purchased from processing plant	1.06	1.06	1.06	1.06

[a] Electricity consumption estimated for 1.52 kg of pulses delivered from farm

[b] Electricity consumption estimated for 1.33 kg of pulses processed

[c] Electricity consumption was assumed equal to decorticating operation due to lack of data

[d] Glyphosate was used for dry bean because of its effectivity on most weed species (Morishita and Lyon) Actual weed control chemical may vary.

[e] Farming stage includes tillage processes from EcoInvent database such as no-till planting and application of plant protection chemicals for chickpea, dry pea, and lentil and ploughing, cultivating, currying, harrowing, swath, application of plant protection for dry bean. Combine harvesting was used for all pulse crops.

[f] Application rate and type of fungicide was obtained from McKelvy (2020). “Pesticide, unspecified” was used as surrogate process.

The pulse production includes herbicide and fungicide applications, and pre-harvest chemical desiccation using Paraquat (Miller et al., Personal Communication). Fungicide applications are particularly important for chickpea production. Herbicides, pesticides, and respective application rates were selected based on data reported by Brouwer et al. (2015), Kandel et al. (2013, 2018), and Schatz and Endres (2009) and available background data in the EcoInvent database. The application rate for Paraquat (a desiccant) was obtained from Syngenta's (2019) website. Application rates of all chemicals were modeled in OpenLCA as mass of active ingredient (a.i.) per hectare (Table 2.1).

Pulses require rhizobium bacteria to facilitate nitrogen fixation (Kandel et al., 2013). These bacteria are introduced to the soil through inoculants applied either directly to the soil or through seed treatment and persist in soil over time. The exact LCI of inoculant manufacturing was unavailable but consists primarily of rhizobia culture and peat-based carrier (MacWilliam et al. 2014b). Therefore, process for mining peat moss was used as a surrogate process for inoculants.

Field application of fertilizers often leads to nutrient loss in the form of denitrification, leaching, and ammonia volatilization. Considering their contribution to GWP, FE, and ME, accounting for these nutrient losses in LCA model is crucial for accurate analysis. Direct emissions from nitrogen fertilizer application were estimated using IPCC tier-2 method while IPCC tier-1 method was used to estimate indirect emissions (IPCC, 2006). The N_2O emission factor of 0.21% estimated by Dusenbury et al. (2008) for wheat-pea cropping system in the semiarid northern Great Plains was used in the IPCC tier-2 method for direct emissions. This emission factor was less than the default emission factor of 1% suggested by IPCC (2006). Lower fertilizer induced N_2O emissions in the semiarid regions were also confirmed by Sainju et al. (2020, 2012) and Thies et al. (2020). Phosphorus applications often result in loss of soluble phosphorus through leaching and runoff. These pathways were modeled using the method provided by Potter et al. (2006). Post-application fate of crop protection chemicals as well as desiccants used prior to harvest were modeled as emissions to soil.

2.2.2.1(b) Seed production and fertilizer transportation

In 1997, annual seed expenditure by farmers in the United States had reached $7 billion, making it the largest seed market in the world (Fernandez-Cornejo, 2004). This $6.5 billion increase in expenditure, compared to 1960, was largely attributed to increase in the share of seed purchased from commercial sources as a result of technological developments and plant breeding techniques. This makes seed production, processing, and transport a crucial process in terms of LCA.

Commercial seed production processes are proprietary and therefore, are not available in the public domain. In absence of these data, a seed production process ‘Pea seed production, for sowing | pea seed, for sowing | Cutoff, U’ available in EcoInvient 3.4 database was adapted for this study. The unit process included processes such as pre-cleaning, cleaning, drying, chemical dressing, bag filling, and storage. Four distinct seed production processes were created, each for a specific pulse crop modeled (dry beans, chickpeas, lentils, field peas). The source of seed production and electricity was replaced with relevant crop production processes modeled in OpenLCA and US electricity generation and distribution network, respectively. However, only the source of these processes was changed. We did not change the life cycle inventory data of any input processes.

The 2017 Commodity Flow Survey published by US Bureau of Transportation Statistics was used to determine average transportation distance and contribution from various modes of transportation. In the United States, single mode transportation dominated the sector contributing 92.1% of total mass moved and 81% of total value of shipment. However, about 71% of mass (73% of value of shipment) was moved by trucks in the United States. Therefore, transportation of seeds was modeled as freight transport by road. The average transportation distance of 196 km between seed production plants and the seed distributor was used (Bureau of Transportation Statistics, 2018).

Commercial, conventional agriculture depends heavily on fertilizer use. Production and application of fertilizers dominate the impacts associated with fertilizer use in agriculture (Hasler et al., 2015). To account for contribution of fertilizer production, unit processes in EcoInvent 3.4 database for nitrogen, phosphorus, and potassium fertilizers were used. These processes included production of ammonium nitrate phosphate, monoammonium phosphate, and production of potassium fertilizers from various sources. The transportation distances were modified to represent the United States transportation sector. The transportation of fertilizers from production plant to the distributor was modeled as freight by road to a distance of 214 km (Bureau of Transportation Statistics, 2018).

2.2.2.2 Processing Stage

The processing stage in the LCA model included transportation of harvested crop to the processing plant, processing of pulses, and bagging. Harvested pulses may need to be cleaned, dried, sorted, split, milled, decorticated, and fractioned before they are bagged and shipped to the retail markets (USA Dry Pea & Lentil Council, 2019). The processing steps depend on intended use of pulses and sometimes, additional steps such as roasting, puffing, and grinding may be necessary.

The transportation distance between a farm and grain elevator varies depending on proximity to the pulse processing plant. Data specific to transportation distances of pulses are not available. However, O'Donnell (2008) reported that wheat is usually grown within 100 km from processing plants in northwest and central United States. Because pulses are grown in northwest United States and most of the machinery that processes pulses is also designed to handle wheat (Bühler, 2019a), a transportation distance of 100 km was adopted for this study.

The output of the processing stage in this study was raw, processed pulses, packed in 1 kg bags. Pulse processing steps included in the model involved destoning, grading, decorticating, sorting using optical sorter, and splitting (Wood and Malcomson, 2011). Electricity consumed for each processing step was calculated using technical specifications of machinery obtained from Bühler (2019a, 2019b, 2019c, 2019d) and the approach presented by Stössel (2018) was used to fill data gaps at processing stage. The resulting electricity consumption was first normalized for 1 kg of pulses processed using the throughput specified in technical specifications. When throughput was unavailable, an average of available data was used. Technical specifications were unavailable for splitting operations. Therefore, electricity consumption equal to decortication process was assumed for splitting because of similarities in the processes.

The pulse processing results in considerable losses in the form of husk, powder, broken, shriveled, and unprocessed pulses. These losses can amount to up to 25% of total pulses processed (Patras et al., 2011). However, stones and other debris collected during harvesting were not considered in the losses estimated by Patras et al. (2011). In absence of specific data, it was assumed that stones and debris accounted for 12.5% (half of losses) of harvested pulses hauled from the farm. Therefore, electricity consumption for destoning was estimated for 1.52 kg of pulses brought in for processing while that for other operations was adjusted to 1.33 kg of pulses processed (Table 2.1).

The decortication (also called dehulling) primarily removes seed coat; however, small broken pulses and powder is also removed during this process. Pulses can be decorticated using either a wet or dry milling process. The wet process is primarily used to produce decorticated and split pulses, while dry decortication is used to produce both split and whole pulses (Wood and Malcomson, 2011). Because splitting was modeled as a separate process in the study, we assumed decortication by dry process. The dry decortication process requires prior conditioning with water or tempering with oil followed by drying to ease seed coat removal and to avoid breakage, especially for chickpea and field pea that are hard to decorticate (Wood and Malcomson, 2011). Lentil and dry bean species are easy to decorticate and are processed directly without conditioning or tempering.

For chickpea and field pea, conditioning prior to decortication was modeled assuming addition of water at the rate of approximately 10% (w:w), soaking for 4 to 8 hrs, and subsequent drying to 7 to 11% moisture content (Wood and Malcomson, 2011). For 1.33 kg of chickpea and field pea processed, 0.133 kg of water was added. It was assumed that the pulses were harvested at 12% moisture content (USA Dry Pea & Lentil Council, 2019) and all water added during conditioning was absorbed. The amount of water evaporated during drying (0.1613 kg) was estimated by mass balance. The output of the processing stage included 1 kg of pulses packed in a low-density polyethylene (LDPE) bag transported to retails stores. Weights of empty packaging bags of pulses were measured and modeled as 6.06 g of LDPE bag per kg of final product.

2.2.2.3 Retail Stage

The processes in retail stage included transportation of packaged pulses from processing plants to retail stores, storage of these pulses at the stores, food losses at the retail, electricity consumption by the establishment, and land occupation. Input data used for the retail sector are presented in Table 1. The output of retail stage model was 1 kg of pulses stocked at the retail store. According to the USDA Economic Research Service (2019) on an average 5.88% of legumes are lost between and retail and consumer level. These losses were attributed to the retail stage and therefore, input to the LCA model was set to 1.0625 kg of pulses.

The transportation distance for processed and packaged pulses depends on locations of processing plants and retail stores, and regional consumer demand for pulses. Transportation data specific to pulses were not available. However, according to the Bureau of Transportation Statistics (2018) food manufacturing industry transported the food products to an average distance of 452 km. This transportation distance was adopted for processed and packaged pulses, with trucks as the primary mode of transportation.

Data for electricity consumption by retail stores were obtained from 2017 Annual Retail Trade Survey (ARTS) (U.S. Census Bureau, 2017). The total cost of electricity purchased by grocery stores was $5,594 million in 2017. In the same year, average annual retail price of electricity for commercial sector was 10.66 cents per kWh (U.S. EIA, 2020a). These data were used to estimate electricity consumption by grocery stores in kWh in 2017. However, these estimates represented electricity consumption by all grocery stores in the United States. The electricity consumption was allocated to a kilogram of pulses stocked in the grocery store using allocation based on shelf space occupied by a product and per capita loss-adjusted availability of legumes at retail stores. Dry beans occupy about 0.06% of consumer facing shelf space area at a supermarket (Willlard Bishop, 2016). In the absence of more granular data, this estimate was adopted to allocate retail stage burdens to all pulses. The total mass of pulses sold by the retail sector was estimated using per capita loss-adjusted availability of pulses at retail sector (5.40 kg/year) and 2018 estimate of US population (327 million) (U.S. Census Bureau, 2018; USDA Economic Research Service, 2019). The average of land occupation for superstore, neighborhood markets, and warehouse clubs was 11,179 m^2 (Walmart Inc., 2019), which was allocated to a kilogram of pulses using the same allocation factor estimated for electricity use.

2.2.2.4 Consumer Stage

The consumer stage is the last stage in the cradle-to-grave LCA model. It included purchase of pulses from retail stores, transportation for grocery shopping, cooking, and consumption of pulses, and associated waste to landfill. The reference flow of the consumer stage on the dry basis was 56 g of dry bean, 58 g of chickpea and 60 g each of field pea and lentil cooked and consumed at US household. The reference flow represented average weekly consumption of pulses in the United States (HHS and USDA, 2015). Accounting for an estimated 10% plate wastage (USDA Economic Research Service, 2019) in the form of uneaten cooked pulses, the quantity purchased from retail was 62, 54, 66, and 66 g for dry bean, chickpea, field pea, and lentil, respectively.

Transportation at the consumer stage involved passenger car transportation for grocery shopping. In the United States, the average distance to a grocery store in 2015 was 3.77 km (USDA Economic Research Service, 2015). This included distances for average US households (3.45 km), SNAP recipients (3.16 km), and food insecure and WIC households (4.70 km). However, it was reported in the same USDA study that consumers often travelled to their preferred grocery store, often farther than the closest one. Therefore, average distance of 5.52 km (average US household- 6.10 km, SNAP participants- 5.41 km, food insecure households and WIC 5.07 km) was used in the model for grocery shopping.

Consumption of pulses at the consumer stage varied by the pulse variety. The loss-adjusted per capita availability of dry beans and dry peas and lentils at consumer level was 2.90 and 1.65 kg per year respectively (USDA Economic Research Service, 2019). Per capita loss-adjusted availability of dry peas and lentils was disaggregated into chickpeas, lentils and field peas based on proportion of these species in total domestic availability of chickpea, lentil, and field pea (Table A.1). The burden of transportation was allocated to each pulse variety (Table A.1) using percentage of total household expenditure on chickpeas, lentils, field peas, and dry beans estimated using average 2017 national average retail price for dry beans and household consumption of each pulse variety (U.S. Bureau of Labor Statistics, 2018; U.S. Census Bureau, 2019; USDA Economic Research Service, 2019). The retail price was available only for dry bean, which was adopted for other three pulse species.

For the base case scenario, it was assumed that cooking pulses involved boiling and simmering pulses in an open vessel on electric stove (OVC). The electricity consumption and water requirements for cooking depend on pulse variety (USA Dry Pea & Lentil Council, 2019). Dry beans and chickpeas require soaking which reduces the cooking time and consequently electricity consumption. Pulses such as lentils and field peas can be cooked without soaking. The water requirement for soaking and cooking and cooking time are provided in Table A.2. Data provided by USA Dry Pea & Lentil Council (2019) included volumetric measurements of pulses and water. These were converted to mass measurements using density of pulses and water.
The base scenario in the study was open vessel cooking (section 2.2.2.4 (a)), which involved boiling and simmering pulses in an open vessel on an electric stove. Two other methods of

cooking pulses were evaluated in this study, representing two alternative scenarios. These were cooking in stovetop pressure cooker and in electric pressure cooker (section 2.2.2.4(b)). The LCI for the consumer stage, including the differences between study scenarios, is provided in Table 2.2.

Table 2.2- Life cycle inventory for consumer stage for open vessel and pressure-cooking scenarios

Pulse variety	Inputs							Reference Flow, kg
	Mass of pulses, kg	Water (L)			Electricity, kWh		Grocery Travel, km	
		Cooking	Soaking	Dishwasher	Cooking	Dishwasher		
Open Vessel Cooking (OVC)								
Chickpea	0.064	0.225	0.225	0.011	1.628	0.001	0.004	0.058
Dry bean	0.062	0.150	0.225	0.057	1.620	0.004	0.020	0.056
Field pea	0.066	0.150	-	0.014	0.685	0.001	0.005	0.060
Lentil	0.066	0.188	-	0.007	0.355	0.0004	0.002	0.060
Pressure Cooking, Stovetop Pressure Cooker (SPC)								
Chickpea	0.064	0.225	0.225	0.011	0.588	0.001	0.004	0.058
Dry bean	0.062	0.225	0.225	0.057	0.303	0.004	0.020	0.056
Field pea	0.066	0.225	-	0.014	0.648	0.001	0.005	0.060
Lentil	0.066	0.225	-	0.007	0.327	0.0004	0.002	0.060
Pressure Cooking, Electric Pressure Cooker (EPC)								
Chickpea	0.064	0.225	0.225	0.011	0.223	0.001	0.004	0.058
Dry bean	0.062	0.225	0.225	0.057	0.117	0.004	0.020	0.056
Field pea	0.066	0.225	-	0.014	0.366	0.001	0.005	0.060
Lentil	0.066	0.225	-	0.007	0.094	0.0004	0.002	0.060

2.2.2.4(a) Open vessel cooking (OVC)

The total cooking time in OVC included time required to bring the water to boil and simmering time specific to the pulse variety. In OVC scenario, the energy required to bring the water to boiling point was estimated using Equation 1. On an average the household electric stove draws between 1200 and 3000 watts of power (Direct Energy, 2019). An average power of 2100 watts (2100 J/s) was used to determine time required to bring the water to boiling from an initial temperature of 25°C. Electricity consumption (kWh) to fully cook pulses was estimated assuming 20% of average cooking range power requirement (simmering setting) and simmering times provided in Table A.2. Cooking efficiency of 39% for electric coil, estimated as the ratio of energy transferred to water and energy input, was used to account for specific heat capacities of water and vessel and radiative energy losses (Karunanithy and Shafer, 2016).

$$Q = m \times C \times (T_f - T_i)$$

Equation 1

Where,
Q = energy required to raise temperature of water (J)
m = mass of water (g)
C = specific heat of water (J/g-°C)
T_f = final temperature of water (°C)
T_i = initial temperature of water (°C)

Electricity and water consumption at the consumer stage also included dishwashing. A typical dishwasher in a US household consumed between 270 and 307 kWh of electricity per year and between 13 and 19 liters of water per cycle (Appliance Standard Awareness Project, 2017). The dishwasher electricity consumption per cycle was estimated assuming one cycle per day. This electricity and water consumption were allocated to pulse species using the economic allocation provided in Table A.1.

2.2.2.4(b) Pressure cooking (Stovetop, SPC and Electric, EPC)

A pressure-cooking scenario was evaluated to estimate the impact of cooking method on sustainability metrics. Pressure cooking substantially reduces cooking time, consequently reducing cooking energy use. However, besides cooking time, energy savings also vary with the type of pressure cooker (stovetop or electric) and related energy losses. The heating components of electric pressure cookers are insulated making them more energy efficient than stovetop pressure cookers (Reynolds et al., 2018). These differences were captured by creating scenarios for stovetop (SPC) and electric (EPC) pressure cookers. It was assumed that temperature control on the cooking range was set to the medium heat setting (50% of average power requirement of electric cooking rage) for stovetop pressure cooker with the cooking efficiency similar to OVC. For electric pressure cooker, on the other hand, energy efficiency of 95% was assumed between heating element and wall power outlet with an average power consumption of 1071 W. The power consumption of electric pressure cooker was estimated from specifications provided by

Instant Brands Inc (2020a). Data for cooking time of pulses were obtained from FastCooking (2019) and Hawkins Ventura (2003) for SPC (Table A.3) and from Instant Brands Inc (2020b) for EPC (Table A.4). It was assumed that the ratio between volume of cooking water and pulses reported by Hawkins Ventura (2003) was independent of pressure cooker type. The cooking time varied with pulse variety and is substantially reduced if pulses were soaked prior to cooking. Similar to OVC, it was assumed that only chickpea and dry bean were soaked prior to cooking, to ensure that only the influence of cooking method was evaluated. The amount of water required for soaking chickpeas and dry beans was adopted from the OVC scenario. Electricity consumption for the pressure-cooking scenario was estimated using the same method used in the OVC scenario. However, pressure cooking did not require bringing the water to a boil before adding the pulses. Therefore, cooking time in this scenario reflected time required to cook pulses that were started with room temperature water.

2.2.3 Uncertainty Analysis

Data used for life cycle impact analysis is based on mean estimates of parameter values which carry uncertainty that could alter the conclusions. Therefore, an uncertainty analysis was performed using Monte Carlo Simulations (MCS) to increase confidence in the interpretation of results. Data for most parameters in the model included means and range. Therefore, uncertainty for these foreground model parameters was defined as a triangular distribution, with the exception of crop yield. A normal distribution was defined for the crop yield using standard deviation estimated using USDA-NASS data (USDA National Agricultural Statistics Services, 2017). Background processes from EcoInvent database were adopted in the model without changing their uncertainty characteristics. Uncertainty in impact characterization factors is not included in the evaluation, therefore this assessment represents a lower bound on uncertainty of the results.

2.2.4 Sensitivity to the reference flow

It was discovered during the initial runs of the cradle-to-grave model that the environmental impact categories were highly sensitive to the mass of pulses cooked in a batch. In OVC and both pressure cooking scenarios the reference flow of 60 g represented average weekly consumption of pulses. The influence of consumer stage reference flow on environmental impact categories was assessed by changing this reference flow to 1 kg of pulses while maintaining cooking method to open vessel cooking (OVC-RF1). This reference flow represented cooking one large batch of pulses to be consumed over approximately four months at current weekly consumption rate of 60 g. However, this required freezing cooked pulses and reheating them before consumption, most likely using a microwave. Annual household refrigerator and microwave electricity consumption obtained from U.S. EIA (2015) was attributed to each pulse variety using economic allocation factors used for passenger travel for grocery (Table A.1). Safe storage period of 2 to 3 months estimated for frozen soups and stews (FoodSafety.gov, 2021) was adopted for pulses to estimate increased food wastage. Assuming that four-month supply of cooked pulses can be safely stored only for maximum of 3 months, food wastage of pulses was increased to 25% for this scenario. However, it was assumed that pulses were stored for four months before they were discarded. Therefore, refrigerator and microwave electricity consumption were estimated assuming four-month refrigerator use and 12 instances of microwave use (Table 2.3).

Table 2.3- Electricity and water consumption at consumer stage for the reference flow of 1 kg

Pulse variety	Inputs							
	Mass, kg	Water, kg			Electricity kWh			
		Cooking	Soaking	Dishwasher	Cooking	Dishwasher	Refrigerator	Microwave
Chickpea	1.333	4.662	4.662	0.132	2.129	0.008	0.069	0.001
Dry bean	1.333	3.231	4.847	0.686	1.968	0.042	0.358	0.006
Field pea	1.333	3.019	-	0.171	1.009	0.010	0.089	0.001
Lentil	1.333	3.773	-	0.087	0.760	0.005	0.046	0.001

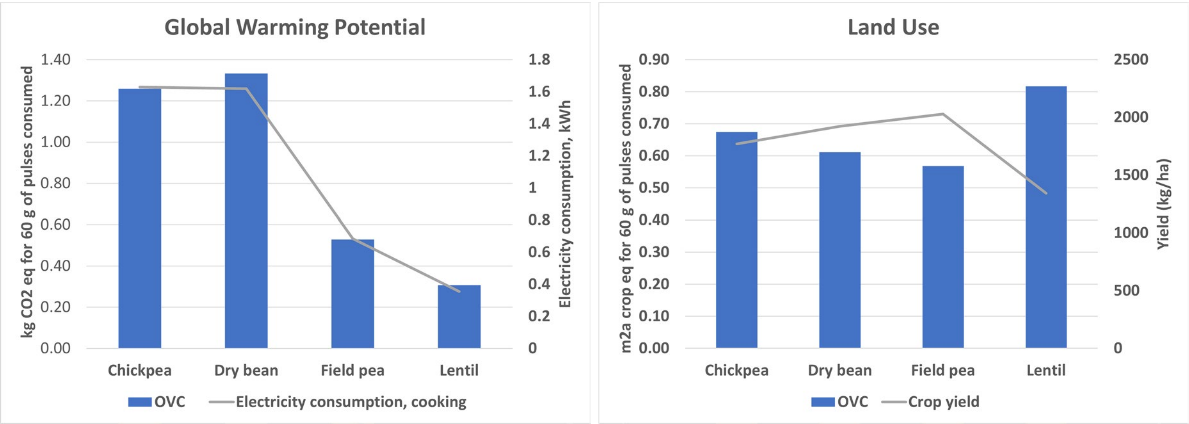
2.3 Results and discussion

Cradle-to-grave environmental impact of pulses was assessed in this study The base scenario, OVC, included cooking pulses on an electric stove in an open vessel. SPC and EPC scenarios evaluated the impact of cooking method while the OVC-RF1 scenario estimated the impact of mass of pulses cooked per batch on environmental impact of pulses. We also evaluated inter-varietal variability resulting from the differences in crop production practices and time required to cook the pulses.

2.3.1 Open vessel cooking

2.3.1.1 Impact category scores

The GWP for 60 g (dry basis) of pulses consumed in a US household was 1.26, 1.34, 0.53, and 0.31 kg CO_2e for chickpeas, dry beans, field peas, and lentils, respectively (Figure 2.2). Fossil fuel consumption in ReCiPe 2016 is reported as fossil fuel scarcity and expressed as kg oil eq. The FRS ranged between 0.08 and 0.34 kg oil eq per 60 g of pulse crop (chickpeas: 0.32, dry beans: 0.34, field peas: 0.14, lentils: 0.08 kg oil eq). The LU measured in m^2a crop eq was 0.69 for chickpeas, 0.63 for dry beans, 0.58 for field peas, and 0.82 for lentils. Throughout the cradle-to-grave processes, WC was estimated at 7.41, 7.75, 3.22, and 2.12 L for chickpeas, dry beans, field peas, and lentils, respectively. The FE, resulting primarily from phosphorus fertilizer application, was 1.37, 1.43, 0.59, and 0.36 g P eq for chickpea, dry bean, field pea, and lentil, respectively. ME ranged between 0.021 g N eq for lentil and 0.092 g N eq for dry bean. The ME for chickpea and field pea was 0.088 and 0.037 g N eq, respectively.



(a) (b)

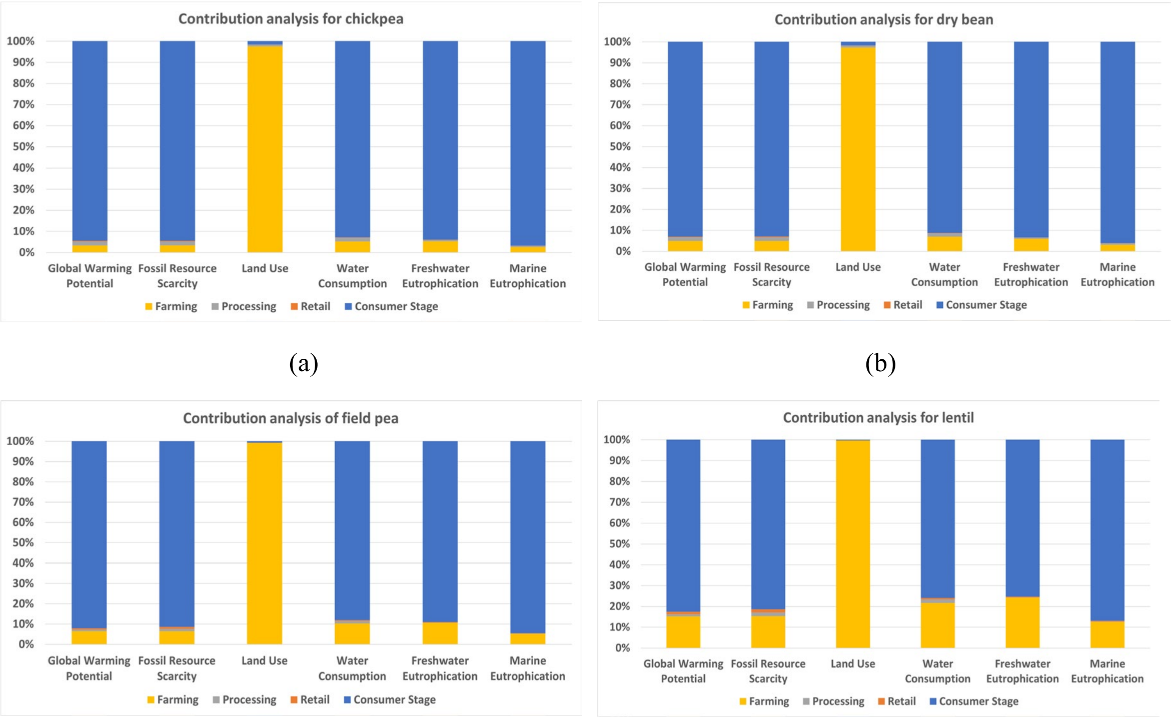
Figure 2.2- Environmental impact of 60 g of pulses estimated for OVC scenario for following impact categories (a) GWP, (b) LU. Graphs for other impact categories are presented in Figure A.1 in Appendix A.

2.3.1.2 Inter-species variability and contribution analysis

Inter-varietal variability within environmental impact categories was associated with factors such as crop management practices, fertilizer application rates, crop yield, and cooking time. With the exception of LU, the greatest contribution to all other impact categories resulted from the consumer stage, which involved purchasing and cooking pulses and plate waste. The consumer stage contributed at least 83, 81, 76, 75, and 87% of total impact for GWP, FRS, WC, FE, and ME, respectively.

2.3.1.2(a) Global warming potential and fossil resource scarcity

The contribution of the consumer stage to GWP and FRS varied with pulse variety. However, for both impact categories contribution from consumer stage was the greatest for chickpea and the least for lentil (Figure 2.3). Greater contribution from the consumer stage to these impact categories as well as inter-varietal variability in impact category scores could be attributed to electricity consumed during cooking. Electricity was utilized at the consumer stage primarily for cooking and for running the dishwasher. However, cooking contributed to approximately 99% of total electricity consumption at the consumer stage for which, the driving factor was cooking time.



(a) (b)

(c) (d)

Figure 2.3- Results of contribution analysis for (a) chickpea, (b) dry bean, (c) field pea, and (d) lentil, for OVC scenario

Cooking pulses in open vessels requires brining water to boil followed by simmering until pulses are cooked through. The time required to boil water (range: 57 seconds to 1 min 26 seconds) and consequently, associated electricity consumption did not vary substantially. This was because only small quantities of pulses were cooked, which required mass of water that ranged between 150 g and 225 g. On the contrary, post-boil simmering time varied between 19 minutes for lentil to 90 minutes for chickpea and dry bean. This difference in cooking times resulted in the proportional inter-varietal variability in electricity consumption, which was reflected in fossil fuel scarcity scores.

Electricity production in the United States relies heavily on fossil fuels, primarily natural gas, and coal. In fact, about 63% of total electricity generated in the US in 2019 was produced using fossil fuels (U.S. EIA, 2020b). Upstream emissions associated with electricity production were responsible for increasing overall GWP impact scores of pulses and contribution of consumer stage. For example, approximately 94% of total GWP of chickpea was associated with electricity production from all sources, while at least 78% of GWP resulted from electricity production that relied on coal and natural gas.

The GWP and FRS scores of pulses followed a general trend similar to electricity consumption at the consumer stage. However, a slight anomaly was observed in GWP and FRS scores of chickpeas and dry bean. The GWP and FRS of dry bean was 6.4 and 6.3% greater compared to chickpea when the electricity consumption at the consumer stage for these were comparable. Greater GWP and FRS observed for dry bean was attributed to marginally greater contribution from the cradle-to-farm stage to these impact categories. Unlike other pulse species, dry beans were grown using conventional farming methods. Increased fossil fuel use required for conventional farming and related greenhouse gas emissions marginally increased the contribution of farming stage to these impact categories and overall impact scores.

2.3.1.2(b) Land use

In contrast to other impact categories, the primary contributor to the LU was crop production. The factor responsible for this contribution as well as for the inter-varietal variability in LU scores was crop yield. The LU score was inversely related to the yield because greater yield increased resource utilization efficiency at the farm. The crop yield varied with pulse variety ranging between 1342 kg ha^{-1} for lentil and 2029 kg ha^{-1} for field pea, respectively. Consequently, the LU was the greatest for lentil and the least for field pea (Figure 2).

2.3.1.2(c) Water consumption

The greatest contribution to total WC came from the consumer stage, amounting to 76% of total WC for lentil and more than 88% of total WC for other pulse species. Similar to GWP and FRS, electricity consumption at the consumer stage and associated upstream water use were responsible for the greater contribution from consumer stage. For example, water use related to electricity consumption at the consumer stage accounted for approximately 85% of total water use. Only 7.3 and 7.7% of water use was associated with cooking and dishwashing, and other upstream processes, respectively. The electricity and water use at the consumer stage also influenced inter-varietal variability in WC scores. Chickpea and dry bean required longer cooking time and needed water for soaking which increased their WC compared to field pea and lentil.

3.3.1.2(d) Freshwater and marine eutrophication

The contribution of the consumer stage to the total impact category scores ranged between 75 and 94% for FE and between 87 and 97% for ME. For both impact categories, contribution from the consumer stage was the least for lentil and the largest for chickpea. A greater contribution of consumer stage was primarily because of electricity use at the consumer stage and associated upstream emissions of NOx and phosphate compounds.

However, phosphorus and nitrogen fertilizer application rates and crop yield at the farming stage influenced total eutrophication impact scores as well as contributions from the farming stage. Dry bean, for example, required more nitrogen fertilizers compared to other pulse species. This resulted in the largest contribution to marine eutrophication (0.0029 g N eq per FU) scores for dry bean from the farming stage. In contrast, the marine eutrophication scores of other three pulse species at the farmgate were lower than the dry bean because of lower nitrogen demand. However, despite identical phosphorus and nitrogen application rates, lower crop yield of lentil increased their FE (0.088 g P eq per FU) and ME (0.0026 g N eq per FU) scores compared to chickpea (FE: 0.073 g P eq per FU, ME: 0.0022 g N eq per FU) and field pea (FE: 0.063 g P eq per FU, ME: 0.0022 g N eq per FU) at the farmgate.

2.3.2 Pressure cooking

Switching cooking method from open vessel cooking to pressure cooking reduced GWP of pulse species by 5 to 86%. FRS by 5 to 85%, WC by 1 to 78%, FE by 5 to 86%, and ME by 5 to 88 (Table 4). The lower impact scores observed for pressure cooking scenarios were attributed to shorter cooking times and associated energy savings. However, shorter cooking times did not always result in proportional decrease in the electricity consumption, especially for SPC scenario. Despite 62% reduction in the cooking time for field peas in SPC (OVC- 39 minutes, SPC- 15 minutes), the electricity consumption decreased only by 5%. This discrepancy was primarily because of assumptions made regarding heat control setting on a cooking range, which was assumed to use 20% (low heat) and 50% (medium heat) of available heat for OVC and SPC, respectively. Therefore, more heat was required throughout the cooking period to achieve shorter cooking times in SPC, which decreased the magnitude of savings in electricity consumption. Nevertheless, SPC reduced the environmental impact scores of pulses by at least 5% across all impact categories, excluding LU.

The EPC resulted in the lowest impact scores among all cooking methods across all pulse species and impact categories, excluding LU. This was attributed to lower energy demand and improved energy efficiency of pressure cookers compared to OVC and SPC. The electric pressure cookers required an average 1071W power compared to 2100W required for stovetop cooking. Moreover, the energy efficiency of electric pressure cookers was at least 95% resulting in more efficient use of electricity. This lowered electricity consumption for cooking and associated upstream emissions. Electricity consumption for dry beans and chickpeas in EPC, for instance, was at least 61% lower compared to SPC, whereas cooking time remained identical (Table A.3).

Overall, the greatest reduction in impact category scores, compared to OVC, was observed for dry bean, followed by chickpea, lentil, and field pea. While the magnitude of this change was greater for EPC compared to SPC, an identical trend was observed for both scenarios. The magnitude of change in impact category scores compared to OVC depended on the decrease in electricity consumption required for cooking pulses. Compared to OVC, pressure cooking methods offered the greatest savings in electricity consumption for dry bean (SPC- 81%, EPC- 93%), followed by chickpea (SPC- 64%, EPC- 85%), lentil (SPC- 8%, EPC- 74%), and field pea (SPC- 5%, EPC- 47%), which was also reflected in their environmental impact score across all impact categories, excluding LU. The largest contributor to the LU was farming stage, where crop yield was the primary driving factor. Because cooking methods only influenced electricity consumption, only a small to no change in LU was observed for SPC and EPC (Table 2.4).

The pressure-cooking method expedited cooking of all species of pulses, reduced environmental impact of pulses, and marginally decreased the contribution of the consumer stage to the overall impact. However, the contribution of the consumer stage still remained high (Figure A.2 and A.3). The consumer stage in pressure cooking scenario contributed between 52 (EPC, dry bean) and 92% (SPC, field pea) of total GWP (compared to 83 to 95% for OVC) and between 52 (EPC, dry bean) and 91% (SPC, field pea) of total FRS (compared to 81 and 94% for OVC). This was primarily because in spite of 5 to 93% reduction in total cooking-related electricity consumption, the upstream emissions associated with electricity production still dominated total emissions from the pulse supply chain, increasing the contribution of consumer stage for SPC and EPC.

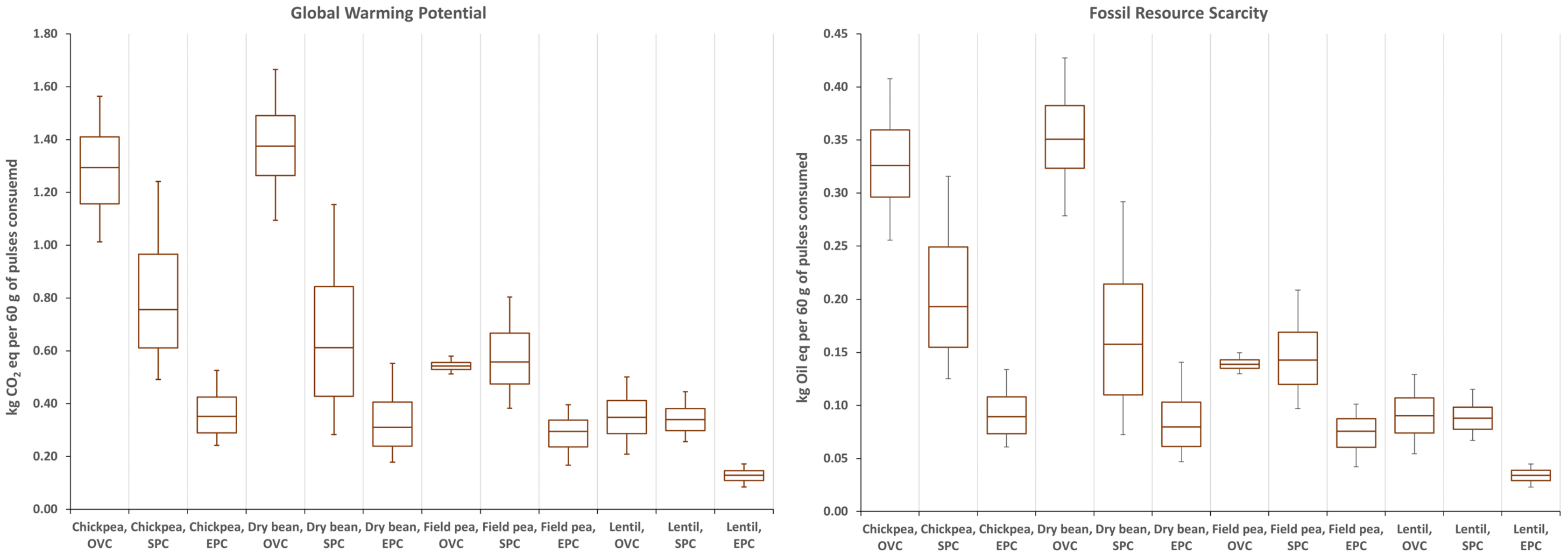
2.3.3 Uncertainty Analysis

Uncertainty analysis was performed to evaluate the robustness of conclusions regarding differences in the environmental impact category scores of pulse species and cooking methods. The results of MCS for GWP and FRS are presented in Figure 2.4. Results for other impact categories are presented in (Figure A.4). Differences in GWP, FRS, FE, and ME scores of pulse species were more prominent for OVC, compared to SPC and EPC. For OVC scenario, there was more overlap of boxes and whiskers for chickpea and dry bean compared to other two pulse species suggesting a higher probability that impact scores of chickpea and dry bean for these four impact categories were comparable to each other but greater than field pea and lentil. Within SPC and EPC, the overlap of box and whiskers for chickpea, dry bean, and field pea indicated that only small to no differences in GWP, FRS, FE, and ME scores. This suggested that inter-varietal variability between chickpea, dry bean, and field pea observed within each pressure-cooking scenario was statistically non-significant. However, there existed a greater probability of lentil having the lowest impact scores across these four impact categories for all three cooking scenarios. The uncertainty analysis also suggested a probability that LU of chickpea, dry bean, and field pea was comparable to each other while that of lentil was marginally greater, and a probability that the differences in water use scores of these pulse species were statistically non-significant.

As expected, the absence of differences in LU in relation to cooking method was confirmed by the uncertainty analysis. Similarly, the uncertainty analysis indicated that the difference in mean WC scores in relation to cooking method were not statistically significant. For GWP, FRS, FE, and ME (impact categories discussed hereafter), the uncertainty analysis confirmed the mixed influence of cooking method on environmental impact. For chickpea and dry bean SPC decreased environmental impact scores across these four impact categories compared to OVC. However, the influence of pressure cooker type on impact categories was more pronounced for chickpea compared to dry bean. This suggested a greater probability for chickpea (and a lower probability for dry bean) that EPC significantly decreased impact category scores, when compared to SPC. The uncertainty analysis also indicated that for field pea and lentil, impact category scores of OVC and SPC scenarios were comparable, but a greater probability existed that EPC lowered environmental impact of these two pulse species.

Table 2.4- Environmental impact for 60 g of pulses cooked in stove top and electric pressure cooker.

Impact category	SPC				EPC			
	Chickpea	Dry bean	Field pea	Lentil	Chickpea	Dry bean	Field pea	Lentil
Global warming potential, kg CO_2 eq	0.50	0.33	0.50	0.29	0.23	0.19	0.30	0.12
Fossil resource scarcity, kg oil eq	0.13	0.09	0.13	0.07	0.06	0.05	0.08	0.03
Land use, m^2a	0.69	0.62	0.59	0.82	0.69	0.62	0.58	0.82
Water consumption, L	3.31	2.44	3.18	2.06	1.86	1.68	2.09	1.16
Freshwater eutrophication, g P eq	0.55	0.35	0.56	0.34	0.26	0.20	0.35	0.16
Marine Eutrophication, kg N eq	0.034	0.022	0.035	0.019	0.016	0.012	0.021	0.008



(a) (b)

Figure 2.4- - Results of uncertainty analysis for (a) GWP and (b) fossil resource scarcity for OVC, SPC, and EPC. The results for other impact categories are presented in Appendix A (Figure A.4)

2.3.4 Sensitivity to consumer stage reference flow (OVC-RF1)

Changing consumer stage reference flow to 1 kg of pulses substantially reduced environmental impact of pulses across all impact categories (excluding land use) even after accounting for increased food waste and electricity consumption. Estimated GWP in this scenario for 60 g of pulses was 0.18, 0.21, 0.10, and 0.10 kg CO_2e for chickpea, dry bean, field pea, and lentil, respectively. The GWP in this scenario was approximately, 86 (chickpea), 84 (dry bean), 82 (field pea), and 68% (lentil) lower than OVC scenario (Figure 5). Similar decrease in scores was also observed for FRS (67 to 86%), WC (49 to 77%), FE (60 to 85%), and ME (72 to 87%). The primary reason of this decrease in environmental impact of pulses was lower electricity consumption. Increasing the reference flow to 1 kg increased cooking electricity consumption as more energy was necessary to boil larger mass of water. However, the simmering time remained unaffected resulting in very small change in electricity consumption that ranged between 0.32 to 0.50 kWh. Moreover, because larger quantity of pulses was cooked in a single batch, total electricity consumption, normalized for mass of pulses cooked, remained between 0.61 to 1.78 kWh/kg of pulses for OVC-RF1 as opposed to 5.36 to 26.21 kWh/kg of pulses for the OVC. This reduction in total electricity consumption also reduced upstream emissions, resulting in lower environmental impact scores across all impact categories, excluding land use. The land use in OVC-RF increased by 18 to 20% compared to OVC. However, the Monte Carlo Simulations indicated that this change in land use was not statistically significant (Figure 2.5, Figure A.5).

A trade-off between the contribution from consumer and farming stage was also observed for this scenario (Figure A.6). Cooking larger quantity of pulses in a single batch decreased the contribution from consumer stage to GWP by 42 to 48 percentage points compared to OVC. It

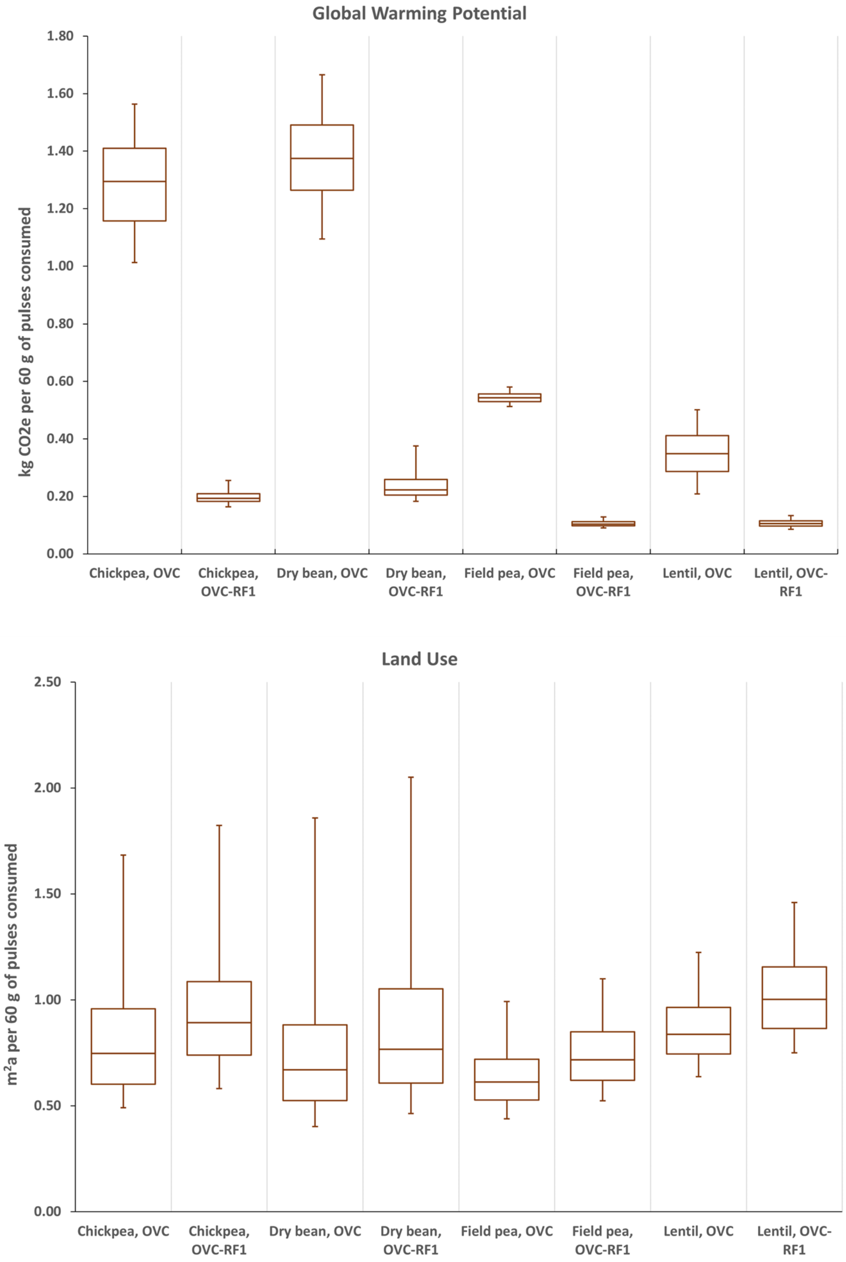


Figure 2.5- Results of Monte Carlo Simulations indicating the influence of consumer stage reference flow on GWP and LU of pulses. The results for other impact categories are provided in Figure A.5 in Appendix A

also increased the contribution from the farming stage to overall GWP, which ranged between 28 and 57% for OVC-RF1 compared to 3 to 15% observed for OVC. A similar trend was also observed for FRS, WC, FE, and ME. A small increase, compared to OVC, in contribution from processing and retail stages to overall GWP (2 to 14 percentage points) and FRS (2 to 13 percentage points) scores was also observed.

Similar to pulses, the influence of batch size and cooking-related energy demand on GWP and FRS was also observed for potatoes and bread. Parajuli et al. (2021) reported that the contribution from the consumer stage for at-home consumption of 1 kg of fresh potatoes was 47% of total cradle-to-grave GWP, primarily because of frying in vegetable oil. For 1 kg of frozen potato fries this contribution was 38%. In case of bread, electricity consumption for refrigerated storage and toasting of bread at the consumer stage contributed as much as 25% of total GWP in a cradle-to-grave analysis (Espinoza-Orias et al., 2011). The most energy-intensive process in bread manufacturing was baking, which accounted for an average of 64% of total energy consumption in the bread supply chain (Braschkat et al., 2003). Moreover, the energy consumption was three times greater for home baking compared to industrial baking, which also increased the GWP of home-baked bread (Braschkat, et al., 2003).

2.3.5 Cradle-to-farmgate impact analysis

The contribution of the farming stage to the most impact categories was lower compared to the consumer stage. However, cradle-to-farmgate impact assessment and contribution analysis can provide insights into influence of farming activities on sustainability of the pulses. It can also facilitate easy comparison between pulses and other crops in term of their environmental impact.

Table 2.5- Environmental impact associated with production of pulses for 1 kg of harvested pulses at the farmgate

Impact Category	Chickpea	Dry bean	Field pea	Lentil
Global warming potential, kg CO_2 eq	0.40	0.61	0.32	0.45
Fossil resource scarcity, kg oil eq	0.11	0.16	0.08	0.12
Land use, m^2a	6.31	5.66	5.40	7.80
Water consumption, L	3.82	4.99	3.09	4.40
Freshwater eutrophication, g P eq	0.69	0.79	0.59	0.84
Marine Eutrophication, g N eq	0.022	0.027	0.018	0.025

The GWP of pulses at the farmgate ranged between 0.32 and 0.61 kg CO_2e per kg of harvested pulses (Table 2.5), with the greatest GWP observed for dry beans, followed by lentil, chickpea, and field pea. A similar trend was also observed for FRS, WC, FE, and FE (Figure A.7). The trend for LU was slightly different. The greatest land use score was observed for lentil, followed by chickpea, dry bean, and field pea (Table 5). Primary contributors to the environmental impact of pulses (excluding LU) were tillage operations, emissions associated with fertilizer and pesticide manufacturing, production of seeds and inoculant, and field emissions related to fertilizer application (Figure 2.6.).

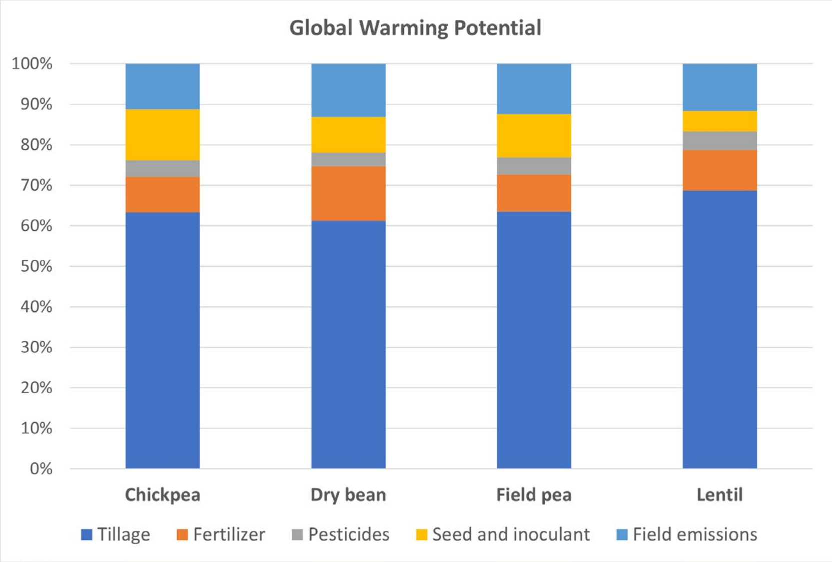


Figure 2.6- Contribution from various farm activities to the GWP associated with production of pulses for 1 kg of pulses harvested at the farmgate. The graphs for other impact categories are provided in Figure A.7 in Appendix A.

The environmental impact scores of pulses as well as the inter-varietal variability were primarily influenced by crop yield, tillage practices, and fertilizer application rates. Conventional tillage and higher nitrogen demand of dry beans increased fossil fuel consumption as well as field emissions. These factors increased the environmental impact of dry bean even when the yield of dry bean was greater than chickpea and lentil. Contrarily, despite identical tillage operations and fertilizer and pesticide application rates, differences in yield resulted in the lowest environmental score for field pea compared to chickpea and lentil. The influence of crop yield was also evident in LU scores of pulses which carried inverse relationship with the yield.

The GWP of pulses estimated in this study was somewhat greater than the values reported by Gustafson (2017) for pulses grown in the United States. For 1 kg of harvested pulses Gustafson (2017) estimated the GWP of 0.31 and 0.26 kg CO_2e for irrigated and dryland pulses, respectively. Greater GWP observed in this study could be attributed to the differences in yield, tillage practices, and use of synthetic fertilizers. Crop yields used in this study ranged between 1,342 and 2,029 kg/ha compared to 2,030 kg/ha used by Gustafson (2017) for dryland pulses. While the mean fertilizer application rate was not reported by Gustafson (2017), exemplary data provided by the author reported that fertilizers were not applied to dryland pulses. On the contrary, we assumed used of nitrogen, phosphorus, and potassium fertilizers in the production of all species of pulses studied. In recent surveys conducted by Bestwick et al. (2018) farmers rarely reported K fertilizer applications, which if removed from the model could lower the environmental impacts of pulses. We also modeled dry beans with conventional tillage practices and greater nitrogen fertilizer application rate compared to other pulse species. These differences in crop management practices between two studies may have contributed to the greater GWP observed in this study.

2.4 Conclusion

The GWP of pulses ranged between 0.12 and 1.34 kg CO_2e for 60 g of pulses produced and consumed in the United States. Impact category scores per functional unit for other impact categories was 0.03 – 0.34 kg oil eq for FRS, 0.58 – 0.82 m^2a for LU, 1.17 – 7.75 liters for WC, 0.16 – 1.43 g P eq for FE, and 0.007 – 0.092 kg N eq for ME. Overall, the environmental impact of pulses varied with pulse variety, cooking method, and mass of pulses cooked per batch. However, the consumer stage dominated the environmental impacts of pulses for all pulse species and scenarios. Electricity consumed during cooking was the principal driving factor for cradle-to-grave impact of pulses and for contribution of consumer stage. Overall, the study identified cooking time and energy use efficiency as two parameters that influenced the electricity consumption at the consumer stage. The direct proportionality of electricity consumption with cooking time and inverse proportionality with energy use efficiency were evident from the results of three cooking method scenarios, where OVC (longer cooking time and lower energy use efficiency) resulted in the greatest environmental impact and EPC (shorter cooking time and greater energy use efficiency) resulted in the least. The benefits of shorter cooking time in SPC were offset by lower energy use efficiency resulting in statistically non-significant change in the environmental impacts for field pea and lentil as compared to OVC.

The study also identified the influence of cooking mass per batch on overall sustainability of the pulses. Even for the open vessel cooking method, increasing the batch size significantly decreased the environmental impact of pulses across all impact categories, excluding LU, despite increased food losses and added electricity demand for refrigeration and microwave use. This was primarily because larger batch size increased the resource utilization efficiency, as larger mass of pulses was cooked with only marginal increase in total cooking time. This substantially decreased electricity consumption per kilogram of pulses. However, the environmental impact of pulses in OVC-RF1 scenario was comparable to EPC for most impact categories.

Overall, the consumer stage, specifically electricity consumed during cooking, was identified as the hotspot in the production and consumption of pulses. Considering cooking pulses in electric pressure cooker or cooking larger mass of pulses per batch resulted in statistically significant reductions in environmental impact category scores, these methods can be adopted to ensure sustainable consumption of pulses.

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Chapter 3 Environmental and nutritional impacts of current and recommended dietary patterns in the US with varying quantities of pulses

Prathamesh A. Bandekar

Abstract

Environmental and human health impacts of current (CDP) and recommended (RDP) dietary patterns were evaluated using Hybrid-LCA approach and Combined Nutritional and Environmental LCA (CONE-LCA) framework. The functional unit (FU) of the study was diet providing 1800 kcal/person/day to females and 2400 kcal/person/day to males. Cradle-to-processor gate life cycle of food commodities was modeled in Environmentally Extended Input-Output LCA (EIO-LCA), while process-LCA was used for post-processor gate life cycle. RDPs included healthy US-style diet (HealthyUS), ovo-lacto-vegetarian diet according to 2015 (Veg2015) and 2010 (Veg2010) USDA dietary guidelines, and vegan diet (Vegan2010) according to 2010 USDA dietary guidelines. Environmental impact of these dietary patterns was compared with a common sex-specific CDP and was measured in terms of global warming potential (GWP); fine particulate matter emissions (PM); ozone formation, human health (Ozone-HH); ionizing radiation (IR), stratospheric ozone depletion (SOD), human carcinogenic toxicity (HCTox); human non-carcinogenic toxicity (HNCTox); water consumption (WC); land use (LU); freshwater eutrophication (FE); marine eutrophication (ME); and fossil resource scarcity (FRS). Human health impact was quantified by combining impact of these emissions on human health and potential protection against diseases offered by RDPs and was measured in terms of disability adjusted life years (DALYs). GWP of current diets for FU was 8.89 kg CO_2e for females and 11.98 kg CO_2e for males. Dominant contributors to the GWP were dairy, beef, fruits, vegetables, and refined grains. HealthyUS diets increased the GWP by at least 32%, while Vegan2010 reduced it by as much as 20% compared to the CDP. Greater GWP of HealthyUS (both sexes) and Veg2010 (female) and lower GWP of Vegan2010 (both sexes) was confirmed by uncertainty and statistical analysis ($p<0.05$). The statistical analysis failed to confirm greater GWP observed for Veg2015 (both sexes) and Veg2010 (males) ($p>0.05$), indicating that these diets had GWP comparable to CDP. Statistically significant increase ($p<0.05$) in all impact category scores (except ME for female) was also confirmed for HealthyUS diet. All RDPs showed a potential to decrease the risk of diseases, which ranged between -56 and -110 µDALYs/capita/day. However, when the detrimental impacts of various environmental emission were considered, reductions in the individual burden of diseases were observed only for Veg2015 (female: -43 µDALYs, male: -31 µDALYs), Veg2010 (female: -55 µDALYs, male: -44 µDALYs), and Vegan2010 (female: -68 µDALYs, male: -53 µDALYs) dietary patterns. Vegan2010 showed the greatest potential to decrease the environmental impact of food systems while simultaneously improve the human health. Pulses provided between 29 and 42% of total protein in RDPs, while contributing less than 1% towards GWP of these diets. They also offered a protection against diseases, which ranged between -3.1 and -9.2 µDALYs/capita/day.

3.1 Introduction

Food is essential for sustaining human life. However, food production, processing, and consumption contributes to greenhouse gas (GHG) emissions and environmental degradation. In 2018 food systems emitted 16 Gt CO_2e to the atmosphere (approximately, one-third of global GHG emissions), with farmgate, pre- and post-production, and land use change contributing 44, 36, and 20%, respectively (Tubiello et al., 2021). In the United States, agriculture was responsible for 11% (595 MMT CO_2e) of national gross GHG emissions in 2020 (EPA, 2022). The greenhouse gas species that dominated these emissions in the USA were N_2O (57%) primarily from synthetic and organic fertilizer application, followed by CH_4 (42%) resulting from enteric fermentation, manure management, and rice cultivation, and CO_2 (1%) associated with urea fertilization and liming (EPA, 2022). Moreover, agriculture also creates competition for land and water, and contributes to resource depletion, non-point source pollution, and damage to the ecosystem and biodiversity. The IPCC (2019) estimated that freshwater consumption by agriculture had reached up to 70% of global freshwater use and that besides increasing the net GHG emissions, agriculture has also increased loss of natural ecosystems such as forests, savannahs, grasslands and wetlands, and biodiversity.

However, the environmental impact of agriculture varies by the food groups often included in human diet. Various studies have highlighted the inefficiencies in production of animal-sourced food and their greater environmental impacts compared to plant-based foods (Al-Shaar et al., 2020; Arrieta and González, 2019; Grant and Hicks, 2018; Heller et al., 2020, 2018; Meier and Christen, 2013). A systematic review of GHG emissions from the fresh food categories (cradle-to-regional distribution center) confirmed a clear hierarchy among the food groups by their origin, where animal-sourced food was associated with higher GHG emissions (Clune et al., 2017). Therefore, a strategic move away from the food of animal origin is necessary in order to reduce global GHG emissions, especially in western diets that rely on animal protein and dairy (HHS and USDA, 2015). Clark et al. (2020) reported that changes to human diets, in addition to reducing GHG emissions from other sectors, are necessary to limit the increase in global average temperature to 1.5 – 2°C by year 2100 as stipulated in Paris Climate Agreement. The authors also noted that plant-rich diets offer 50% chance of achieving the 1.5°C target if the dietary changes are adopted by 2050.

Impact of diets on human health are well-documented. Imbalanced diet or diet of poor nutritional quality can lead to multitude of diseases. Global Burden of Disease Collaborative

Network (2020) estimated that 11.6% of total global burden of disease and 8% of total burden of disease in US was attributable to the dietary risk. The dietary risks included diets low in fruits, vegetables, legumes, whole grains, nuts and seeds, milk, fiber, calcium, seafood omega-3 fatty acids, and poly-saturated fatty acids, and high in red meat, processed meat, sugar-sweetened beverages (SSB), trans fatty acids, and sodium (Global Burden of Disease Collaborative Network, 2020). Various other studies have identified a correlation between increased consumption of red meat and processed meat and elevated risk of diseases such as type 2 diabetes (T2D) (Feskens et al., 2013; Micha et al., 2017b, 2017a), ischemic heart disease (IHD) (Key et al., 2019), stroke and colorectal cancer (Yang et al., 2016; Yip et al., 2018), cardiovascular disease (CVD) mortality (Abete et al., 2014), and breast cancer (Kazemi et al., 2021; Yip et al., 2018). A correlation was also identified between increased consumption of SSB and the risk of T2D and coronary heart disease (CHD) (Bechthold et al., 2019; Micha et al., 2017a) and between increased consumption of fat and the risk of CVD (Zhu et al., 2019). On the other hand, increasing the consumption of fruits, vegetables, pulses, nuts and seeds, whole grains, and soy has been found to offer protection against CHD, stroke, breast cancer, T2D, lung cancer, esophageal cancer, mouth, pharynx, and larynx cancer, and CVD (Afshin et al., 2014; Aune et al., 2017; Bechthold et al., 2019; Kazemi et al., 2021; Micha et al., 2017a; Namazi et al., 2018; Vieira et al., 2016; Viguiliouk et al., 2019; Wu et al., 2015; Yan et al., 2017; Yip et al., 2018). Therefore, increasing the consumption of plant-rich food and substituting animal proteins with plant proteins such as pulses, soy, and nuts and seeds may help not only in decreasing the GHG emissions from the food system but also in improving the human health. It must be noted, however, that animal-sourced food groups such as dairy and seafood have been shown to offer protection against colorectal cancer and CHD (Bechthold et al., 2019; Micha et al., 2017b; Vieira et al., 2017). Hence, careful consideration may be needed to ensure that protection against colorectal cancer and CHD is maintained even when dairy and seafood are eliminated from the diet. Adopting dietary patterns formulated by the authoritative bodies is recommended in such situations, since these patterns provide optimum nutrition.

LCA studies exploring the environmental impacts of dietary changes in and outside US are primarily limited to either producer/processor or retail gate (Barnsley et al., 2021; Behrens et al., 2017; Berners-Lee et al., 2012; Birney et al., 2017; Blackstone et al., 2018; Boehm et al., 2018; Chapa et al., 2020; Hallström et al., 2017; Heller and Keoleian, 2015; Hitaj et al., 2019; Jones and Kammen, 2011; B. F. Kim et al., 2020; Tilman and Clark, 2014; Tom et al., 2016; Weber and Matthews, 2008). The studies that included consumer phase and/or end-of-life activities only measured midpoint impacts of the food systems (D. Kim et al., 2020; Pathak et al., 2010; Veeramani et al., 2017). Environmental impact caused by the food system activities also affect human health through pathways elaborated by Huijbregts et al. (2017). For example, GHG and particulate matter emissions from food systems can be detrimental to human health thereby offsetting any health benefits for diets particularly if high nutritional diet cause higher GHG emissions as shown by Vieux et al. (2013). Therefore, a true impact of food systems can only be quantified by measuring both environmental and human health impact. Including the consumer phase in this assessment is important because it can lead to significant environmental impacts through consumer behavior (Gruber et al., 2016), which must be included when human health impact is to be measured. Moreover, ignoring consumer stage for foods such as pulses, potatoes, and bread with energy intensive cooking (Bandekar et al., 2022; Braschkat et al., 2003; Espinoza-Orias et al., 2011; Parajuli et al., 2021) can also result in underestimation of environmental impacts related to energy production. Therefore, the objective of this study was to compare the environmental and human health impacts of current (CDP) and recommended (RDP) dietary patterns in the United States using life cycle assessment (LCA). Emphasis was also given to ascertaining the contribution of pulses in any potential changes to environmental or human health impact that RDPs may entail. Primary reason for this emphasis was superior nutritional quality of pulses compared to other sources of dietary protein and their potential health benefits (Röös et al., 2020). Compared to other alternatives to meat pulses also require low technological innovation while offering high sustainability gains (van der Weele et al., 2019).

3.2. Material and Methods

A hybrid-LCA approach was used for this study where environmentally extended input-output LCA (EIO-LCA), used for modeling food supply chains up to the processors' gate, was complemented by retail, consumer, and end-of-life (EOL) activities modeled using process-LCA. This approach is known to improve the completeness of the system boundary and resolve the issues associated with truncation problem and the cutoff criteria often used in the process-LCA (Crawford, 2008; Suh et al., 2004). Thus hybrid-LCA may be able to improve both the accuracy and the precision of LCA study by combining the benefits offered by EIO-LCA and process-LCA (Perkins and Suh, 2019).

3.2.1 Goal and scope of the study

The goal of this study was to estimate environmental and human health impacts of RDPs in the United States. In this comparative study the environmental and human health impacts of RDPs were compared with CDPs, considered as a baseline. Sex-specific iso-caloric diets were used for both CDPs and RDPs. The cradle-to-grave system boundary accounted for production and processing of food along with upstream activities, food losses thought out the food supply chains, transportation between supply chain phases, retail storage, purchase and preparation by consumer, and EOL activities. The functional unit (FU) was a diet providing 1800 kcal per day to females and 2400 kcal per day to males. The choice of iso-caloric diets facilitated fair comparison between the selected dietary patters because only the impacts associated with the proportions of various food subgroups was measured. While selecting sex-specific FU also allowed to capture the influence of caloric consumption. In the context of dietary patterns definitions of Food groups and subgroups were adapted from the USDA and HHS (2015), where, for example, food group 'Vegetables' included variety of subgroups such as 'Green', 'Red and orange', 'Starchy', and 'Other'.

We used economic allocation to attribute resources and burdens between the food groups. This was primarily required at the retail and consumer phases where resources such as electricity, natural gas, water, refrigerants etc. were allocated between the food subgroups using revenue share of these subgroups in total retail sale and consumer expenditure on food, respectively. However, monetary data for sectors of interest was also used to disaggregate the economic sectors as necessary. ReCiPe 2016 midpoint and endpoint life cycle impact assessment (LCIA) method (Huijbregts et al., 2017) was used to measure environmental and human health impacts, respectively. Global warming potential (GWP) was primarily used to compare the environmental impact for dietary patterns. However, other midpoint impact categories that affect human health were also included in the study. These included Fine particulate matter formation (PM); Ozone formation, Human Health (Ozone-HH); Ionizing radiation (IR); Stratospheric ozone depletion (SOD); Human carcinogenic toxicity (HCTox); Human non-carcinogenic toxicity (HNCTox); and Water consumption (WC). While land use (LU), freshwater eutrophication (FE), and marine eutrophication (ME), and Fossil Resource Scarcity (FRS) may not directly impact human health, they were included because of their importance in the food system sustainability assessment. Human health impact was measured in terms of Disability Adjusted Life Years (DALYs), a metric that combines years lost because of early death and years lived with disability to quantify the burden of diseases (GBD 2016 Risk Factor Collaborators, 2017; GBD 2019 Diseases and Injuries Collaborators, 2020). Estimates of ReCiPe endpoint method only included DALYs associated with environmental emission that affected human health. Health impacts of RDPs were characterized in terms of DALYs using Combined Nutritional and Environmental LCA (CONE-LCA) framework developed by Stylianou et al. (2016).

3.2.2 Dietary Patterns

Environmental and human health impacts of 4 RDPs were compared against a common CDP. Sex-specific dietary patterns included CDPs (National Cancer Institute, 2019), US Style Health Diet (HealthyUS) and Healthy Vegetarian Eating Pattern (Veg2015) according to 2015 US dietary guidelines (HHS and USDA, 2015), and Vegetarian (Veg2010) and Vegan2010 (Vegan2010) dietary patterns according to the 2010 US dietary guidelines (USDA and HHS 2010) (Table 3.1). CDP and HealthyUS were omnivorous diet while Veg2015 and Veg2010 were ovo-lacto-vegetarian diet. Conversion factors reported by Blackstone and Conard (2020) were used to convert the quantity of food groups from food pattern equivalents to grams. Food group in the diets characterized as ‘Extra Calories’ was first separated into calories from Fats (55%) and Sugars (45%) (National Cancer Institute, 2019) and later into grams of fat (3.87 kcal/g) and sugar (6.43 kcal/g) (USDA-Agricultural Research Services, 2019). The amount of each food subgroup in these diets was regarded as actual consumption, thus quantities purchased minus inedible portion and plate loss. Loss-Adjusted Food Availability Data (Table 3.2) (USDA

Economic Research Service, 2019) was used to account for supply chain losses and to estimate required quantities at consumer (plate loss and inedible portion), retail, and processor stages.

Table 3.1- Current and recommended dietary patterns providing 1800 kcal to females and 2400 kcal to males.

Food Group	Food Subgroup	CDP (g/day)		HealthyUS (g/day)		Veg2015 (g/day)		Veg2010 (g/day)		Vegan2010 (g/day)	
		Female	Male	Female	Male	Female	Male	Female	Male	Female	Male
Fruits	**Fruits**	200	200	265	363	265	363	265	363	265	363
Vegetables	**Dark Green**	12	12	25	34	25	34	25	34	25	34
	Red/Orange	58	72	110	123	110	123	110	123	110	123
	Starchy	54	67	93	115	93	115	93	115	93	115
	Other	84	84	78	100	78	100	78	100	78	100
Grains	**Whole**	41	46	148	204	173	229	148	204	148	204
	Refined	166	234	105	144	105	144	105	114	105	144
Protein	**Beef**	25	45	34	47	0	0	0	0	0	0
	Pork	13	23	17	24	0	0	0	0	0	0
	Poultry	38	52	36	50	0	0	0	0	0	0
	Eggs	25	35	15	21	21	21	28	36	0	0
	Seafood	15	20	32	41	0	0	0	0	0	0
	Nuts/Seeds	9	11	8	10	12	17	25	34	29	39
	Tofu	6	6	3	4	52	80	95	125	78	98
	Pulses[1]	13	14	13	18	26	36	33	43	39	54
Dairy/Dairy Alternatives	**Dairy**	209	268	433	446	433	446	433	446	0	0
	Soymilk	0	0	0	0	0	0	0	0	433	446
Oils	**Oils**	19	25	23	31	23	31	16	22	16	21
Fats	**Fats**	43	60	14	30	16	33	13	28	13	28
Sugars	**Sugar**	59	81	19	41	21	45	18	38	18	38

[1] Dry, uncooked pulse; estimated using average cooked to uncooked conversion factor of 0.36 (Bowman et al. (2013))

Table 3.2- Losses at different stages estimated using the Loss-Adjusted Food Availability Data

Food Group	Food Subgroup	Percentage Loss Between Supply Chain Stages[1]				
		Primary to Retail	**Retail to Consumer**	**Nonedible Share**	**Cooking Loss and Plate Waste**	**Total Loss[2]**
Fruits	**Fruits**	19	12	18	21	54
Vegetables	**Green**	9	14	22	22	52
	Red/Orange	35	10	10	27	61
	Starchy	38	7	11	17	57
	Other	36	9	13	29	64
Grains[3]	**Whole**	0	12	3	20	32
	Refined	0	12	0	22	31
Protein	**Beef**	33	5	0	20	49
	Pork	27	4	0	29	50
	Poultry	37	4	0	18	51
	Eggs	1	9	12	23	39
	Seafood	0	8	0	34	40
	Nuts/Seeds	0	6	0	10	15
	Tofu[4]	9	6	0	24	35
	Pulses	0	6	0	10	15
Dairy/Dairy Alternatives	**Dairy**	1	11	0	23	32
	Soymilk[5]	0	12	0	22	31
Oils	**Oils**	0	20	0	15	33
Fats	**Fats**	0	19	0	31	44
Sugar	**Sugar**	0	11	0	34	41

[1] Estimated from USDA-LAFA data as an average of 2005 – 2010 for oil and fat; 2013 – 2017 for dairy, proteins, and sugar; and 2014 – 2018 for other food subgroups

[2] Estimated from primary weight and loss-adjusted food availability at the consumer

[3] Whole grains included ‘corn hominy and grits’, ‘oat product’, and ‘barley product’. ‘Wheat flour’, ‘rye flour’, ‘rice’, and ‘corn flour and meal’ were separated into whole and refined grains using 14% and 86% for whole and refined grains, respectively, representing proportions in CDP

[4] Assumed same losses as cheese because of similarities in the manufacturing process

[5] Assumed same losses as fluid milk

3.2.3 Hybrid-LCA Approach

3.2.3.1 Input-Output (I/O) Model: Up to Producer/Processor Gate

An academic version of Comprehensive Environmental Data Archive (CEDA) (v4.8) (Suh, 2005) used in the study was an account of the monetary transactions between the US economic sectors for year 2002. These data were first adjusted for inflation to the 2018 US dollars using an inflation factor of 1.47 estimated using Producer Price Index (PPI) data (U.S. Bureau of Labor Statistics, 2021). However, this changed only the value of transactions, while preserving overall structure of the economy. CEDA database follows the North American Industry Classification System (NAICS) to organize economic data for the US industrial sectors. Disaggregation of some of these sectors was necessary to map the post-processor supply chain of food subgroups used in the diet. For example, ‘Animal (except poultry) slaughtering, rendering, and processing’ sector included activities for both beef and pork subsectors and therefore, disaggregation into these subsectors was necessary. Disaggregation was conducted based on revenue share (value of production) of the subsectors in total sector level revenue. Sector and subsector level data from Annual Survey of Manufacture (U.S. Census Bureau, 2021a) was chosen for disaggregation, when available. In absence of these data value of production was estimated using commodity producer prices (explained later) and total production estimates based on per capita primary weight and total US population (USDA Economic Research Service, 2019). For fresh fruits, dry pulses, nuts, and fresh vegetables and subcategories in fresh vegetables (red, orange, starchy, and other) multistep nested disaggregation was necessary. These subsectors were part of ‘Support activities for agriculture and forestry,’ which was first disaggregated into ‘Postharvest crop activities (except cotton ginning)’ and ‘Other support activities for agriculture and forestry.’ Postharvest crop activities subsector was then disaggregated into postharvest activities for fresh fruits, dry beans, nuts, and fresh vegetables. Fresh vegetables subsector was then further disaggregated into four types of vegetables used in the diets (Table B.1). This disaggregation methodology was performed for both inputs and outputs in the CEDA database, while confirming that only necessary inputs are assigned to the disaggregated subsectors to avoid double counting. For example, when postharvest crop activities disaggregated into fresh fruits and other commodities, inputs from fruit farming were assigned only to 'Post harvest crop activities, fresh fruits,' while setting inputs from fruit farming to fresh vegetables, nuts, and dry pulses to zero. Similarly, inputs from newly disaggregated subsectors for fresh vegetables, nuts, and dry pulses to the postharvest activities of the fruit subsector were set to zero. The reference flow (RF) of each disaggregated subsector was also set using the same ratios used for disaggregation.

Disaggregation for soymilk and tofu required a different approach than other industrial sectors because of lack of data for these sectors in publicly available datasets. 'Fluid milk manufacturing sector' in the CEDA was disaggregated into fluid milk and soymilk because alternatives to dairy milk are included in the '311511-Fluid milk manufacturing' as fluid milk substitute (U.S. Census Bureau, 2021b). Production value of dairy milk was estimated using total production of fluid milk in the US (USDA-Agricultural Research Services, 2021) and producer's price for milk (explained later). Data for soymilk was obtained from McCarthy (2019), which included total sale of all milk alternatives. For the purpose of this study all milk alternatives were considered soymilk to match the dietary food groups. Tofu was disaggregated from '311990 All other food manufacturing' sector using the value of production for this sector (U.S. Census Bureau, 2021a) and total sale of Tofu in the United States in 2018 (The Vegan Society, 2021).

The CEDA database is an economic I/O table with a snapshot of monetary transactions between the economic sectors. In mixed unit hybrid-LCA approach used in this study it was necessary to translate the sector level economic outputs into physical units (mass in kg in this study) for the purposes of modeling retail and consumer phases. This was achieved by using producer prices for the food subgroups included in diets. Producer prices were estimated from retail prices and conversion factors (producer price to retail price) provided in the CEDA database (Table B.2). Retail food prices obtained from Quarterly Food-at-Home Price Database (QFAHPD) (USDA-Economic Research Service, 2020) were first adjusted for inflation to 2018 US dollar using consumer price index (CPI) data (USDA-Economic Research Service, 2021), followed by conversion to producer prices (Table B.2). Food groups and subgroups in both QFAHPD and CPI were matched with the food subgroups in dietary patterns. Retail prices for soymilk, tofu, evaporated milk, condensed milk, and dry milk were estimated as an average of retail prices displayed on Wal-Mart.com USA, LLC's online website. These prices were for year 2021 which were converted to 2018 US dollars using CPI. Retail prices for beef and pork were missing in QFAHPD database and therefore, were obtained from National Weekly Retail Activity Reports published by USDA-Agricultural Marketing Service (2021).

For food subgroups such as fruits, vegetables, dairy, and grains that included consumption in various forms (fruits and vegetables- fresh, frozen, canned; dairy- milk, cheese, yogurt, frozen, evaporated, and dry, grains- bread, cereals, pasta, cookies, pastries, oatmeal etc.) retail price was calculated as weighted average price using retail price and total mass at retail. Proportions of grain consumed in various forms for both whole and refined grains (Albertson et al., 2015) was mapped to the I/O sector in the CEDA using NAICS data (Table B.3). For example, yeast breads and rolls; cakes, cookies, pies, pastries; quick breads etc. were considered part of the ‘311810-Bread and bakery product manufacturing’ subsector in the CEDA, while ready to eat cereals, oatmeal, and other cooked cereals were considered under ‘311230-Breakfast cereal manufacturing’ subsector. Retail prices for these grain products were matched with QFAHPD price data. Where exact products could not be found, closest matching product was used as a surrogate. While weighted averages were determined for retail price, producer price was estimated for each variety of food to capture the impact of processing stage on retail to producer price spread. In I/O model these food varieties were first aggregated using their revenue share to the food subgroup and then weighted average retail price was used to convert monetary output to the physical unit.

3.2.3.2 Process Model: Retail and Consumer Phases

Retail and consumer phases were modeled in process-LCA using the physical flows for food groups created at the producer gate in I/O model. ‘EcoInvent 3.6, Allocation cut-off by classification’ database (Wernet et al., 2016) was used for background data in the process model. Resource use at the retail included electricity, natural gas, and water consumptions and refrigerant leakage and recharge. In the United States approximately 38,307 supermarkets were operational in the year 2018 with the median floor area of 3,941 m^2 (42,415 ft^2) (Food Marketing Institute, 2021). Total electricity, natural gas, water consumption, and refrigerant leakage and recharge for the supermarket sector was estimated using the average annual consumption intensities presented in Table B.4 and total supermarket area in the United States. A typical supermarket also sells alcohol and general merchandise, however food accounted for approximately 81% of total supermarket revenue in 2018 (Chanil et al., 2019). Moreover, in typical supermarket refrigeration accounted for 43% of total electricity use, while the rest is considered overheads electricity consumption (ventilation, heating, cooling, cooking, lighting etc.) (U.S. Environmental Protection Agency, 2008). Similarly, space heating and cooking accounted for 87% of natural gas use at a supermarket (U.S. Environmental Protection Agency, 2008). These factors were used to first attribute the electricity and natural gas consumption to the food and then to estimate consumption by end use (electricity consumption for refrigeration and overheads for both natural gas and electricity). In absence of data on retail water consumption profile by end use, all of 81% of total annual water consumption was attributed to the food commodities.

Estimated supermarket resource use attributed to food was allocated between various food subgroups using a revenue-based allocation approach. Per capita loss-adjusted retail weights of food subgroup and their respective retail prices were used to estimate allocation factor for water and overhead electricity and natural gas consumptions. Allocation factors for refrigeration electricity use and recharge were estimated only for food subgroups or commodities that require refrigeration. Refrigeration was considered necessary for dairy, tofu, meats, eggs, poultry, seafood, soymilk, and fat, while nuts and seeds, pulses, oils, and sugar were considered shelf stable. For fruits, vegetables, and grains refrigerant recharge and refrigeration electricity consumption was attributed only to those food types that require refrigeration. For example, refrigeration resources were attributed only to frozen fruits, fruit juices, and fresh fruits such as berries and grapes which require refrigeration. Fresh fruits such as apples, peaches, pineapple, melons etc. were considered shelf stable. In vegetables tomatoes, onions, potatoes were considered shelf stable while in grains only frozen prepared meals containing grains were considered to require refrigeration. The resource estimated for the entire retail sector was normalized with total loss-adjusted retail weights of various food subgroups to determine resource use per unit mass food subgroups (Table 3.3).

Table 3.3- Life cycle inventory at supermarket for 1 kg food commodities

Food Group	Food Subgroup	Refrigerant Charge[2] (kg/kg)	Electricity (kWh/kg)		Natural Gas, Overhead (m^3/kg)	Water (l/kg)
			Refrigeration	Overhead		
Fruits[1]	Fruits	1.02×10^{-4}	0.1901	0.1652	0.0064	0.3553
Vegetables[1]	Green	1.13×10^{-4}	0.2096	0.1652	0.0064	0.3748
	Red/Orange	7.47×10^{-5}	0.1390	0.1015	0.0040	0.2405
	Starchy	6.75×10^{-5}	0.1256	0.0975	0.0038	0.2231
	Other	1.06×10^{-4}	0.1977	0.1505	0.0059	0.3482
Grains[1]	Whole	3.38×10^{-4}	0.6284	0.2249	0.0088	0.8532
	Refined	1.56×10^{-4}	0.2897	0.1883	0.0073	0.4780
Protein	Beef	3.26×10^{-4}	0.6077	0.4791	0.0187	1.0868
	Pork	1.94×10^{-4}	0.3603	0.2841	0.0111	0.6444
	Poultry	1.86×10^{-4}	0.3458	0.2726	0.0106	0.6184
	Eggs	7.19×10^{-5}	0.1339	0.1056	0.0041	0.2395
	Seafood	3.09×10^{-4}	0.5754	0.4537	0.0177	1.0292
	Nuts/Seeds	-	-	0.2998	0.0117	0.2998
	Tofu	2.06×10^{-4}	0.3831	0.3021	0.0118	0.6852
	Pulses	-	-	0.1146	0.0045	0.1146
Dairy/Dairy Alternatives	Dairy	7.79×10^{-5}	0.1451	0.1144	0.0045	0.2594
	Soymilk	3.58×10^{-5}	0.0667	0.0526	0.0021	0.1194
Oils	Oils	-	-	0.2679	0.0104	0.2679
Fats	Fats	1.46×10^{-4}	0.2725	0.2149	0.0084	0.4874
Sugar	Sugar	-	-	0.0959	0.0037	0.0959

[1] Refrigerant charge and refrigeration electricity is attributed only to refrigerated and frozen fruits, fruit juices, vegetables, and frozen foods containing grains.

[2] Typical refrigerants used at the supermarket- R404A

Transportation distances between processor/producer and retail were determined using the Commodity Flow Survey (CFS) data (Bureau of Transportation Statistics, 2018). Distances for commodities in CFS closely matching the food subgroups were selected. For example, transportation distance for ‘Meat, poultry, fish, seafood, and their preparations’ was selected for beef, pork, poultry, and seafood groups, while ‘Milled grain products and preparations, and bakery products’ was used for whole and refined grains. It was assumed that non-perishable and perishable food products were transported by non-refrigerated and refrigerated trucks, respectively. Transportation by road in trucks was selected because according to CFS trucks transported 73% of total value of transported commodities and 72% of total mass in the United States.

Revenue-based approach was used at consumer phase as well to allocate consumer resource use between the food subgroups. Resource use at the consumer phase included electricity consumption for refrigeration, cooking, microwave, and dishwasher use, water consumption for dishwasher use, natural gas and propane consumption for cooking, and distance travelled for grocery shopping. Per capita annual electricity consumption by end use as well as cooking-related natural gas and propane use was estimated from household consumption data (U.S. EIA, 2015) with average household size of 2.5 (U.S. Census Bureau, 2019) (Table B.5). Average travel distance of 5.32 km (USDA Economic Research Service, 2015) and 1.6 trips per week for grocery (Food Marketing Institute, 2019) were used determine annual distance travelled for grocery shopping. Soap and water use of 25 g/cycle (D. Kim et al., 2020) and12 l/cycle (ENERGY STAR, 2021), respectively were used with an assumption of 1 dishwasher cycle per day. The source of cooking energy in the US included electricity, natural gas, and propane (U.S. EIA, 2015). Cooking energy use was first estimated in terms of MJ/year by converting Electricity use in kWh/year and natural gas and propane use in m^3/year to the energy units. This energy use was allocated between all food groups that require cooking, followed by estimation of electricity, natural gas, and propane use in terms of kWh and m^3, respectively.

Dishwasher resource use and travel distance for grocery shopping were allocated between the food subgroups using allocation factors determined based on share of total consumer expenditure on each food subgroup. Resource use for refrigeration, cooking, and microwave were allocated only between the food groups that require these resources (Table 3.4). For example, green vegetables received only the resource use for refrigeration, but it was assumed that the green vegetables were consumed raw and therefore did not receive any cooking or microwave related resource use, while red, starchy, and other vegetables received resource use for refrigeration, cooking, and microwave use. Similarly, refrigeration, cooking, and microwave use was attributed to all perishable proteins (beef, pork, poultry, eggs, seafood, and tofu). Contrarily, only cooking and microwave used was attributed to pulses. It was assumed that shelf stable nuts and seeds were consumed raw and therefore did not require cooking, refrigeration, or microwave use. Unlike the retail stage, it was assumed that all fruits were refrigerated at the consumer. Data on packaging material quantities and recycling rate from Kim et al. (2020) was used in the study.

3.2.4 Estimation of Human Health Impact

Human health impact of dietary patterns was estimated as a combination of cradle-to-grave human health impact of food systems and consumption related potential benefits offered by RDPs, which were healthier alternatives to the CDPs. Endpoint impact category results measured in terms of DALYs in 'ReCiPe 2016 (H) Endpoint' (Huijbregts et al., 2017) were used to quantify cradle-to-grave impact of food systems on human health. Benefits of RDPs were estimated using dietary risk factors (DRF) estimated by Stylianou et al. (2021). These DRFs were an estimation of changes to μDALYs associated with 1 g consumption of various food groups. The negative sign in DRF signifies health benefits offered by a food group, while a positive sign indicated increased risk. CDPs were assumed to be responsible for the current diet related burden of disease. Therefore, only the difference between RDP and CDP for a food subgroup was considered while measuring the benefits of RDPs. However, the benefits of increasing or decreasing a food group consumption can be gained only up to a certain level known as Theoretical Minimum Risk Exposure Level (TMREL) (GBD 2017 Risk Factor

Collaborators, 2018). Consumption beyond TMREL does not change the diet related health risk. Therefore, TMREL were also considered while estimating the combined human health impact of dietary patterns.

Table 3.4- Life cycle inventory per kg of food commodities at consumer phase

Food Group	Food Subgroup	Electricity Use[1,2] (kWh/kg)	Natural Gas Use for Cooking[2] (m^3/kg)	Propane Use for Cooking[2] (kg/kg)	Transportation for Grocery (km/kg)
Fruits	**Fruits**	0.7679	-	-	0.2877
Vegetables	**Green**	0.7869	-	-	0.2948
	Red/Orange	0.7303	0.0579	0.0470	0.1808
	Starchy	0.7028	0.0557	0.0453	0.1740
	Other	1.0875	0.0863	0.0700	0.2692
Grains	**Whole**	0.6520	0.1285	0.1044	0.4012
	Refined	0.3159	0.0538	0.0437	0.3360
Protein	**Beef**	3.4528	0.2739	0.2224	0.8548
	Pork	2.0472	0.1624	0.1318	0.5068
	Poultry	1.9646	0.1558	0.1265	0.4863
	Eggs	0.7611	0.0604	0.0490	0.1884
	Seafood	3.2697	0.2593	0.2106	0.8094
	Nuts/Seeds	0.1366	-	-	0.5348
	Tofu	2.1768	0.1726	0.1402	0.5389
	Pulses	0.3324	0.0655	0.0532	0.2045
Dairy/Dairy Alternatives	**Dairy**	0.6313	-	-	0.2040
	Soymilk	0.2905	-	-	0.0939
Oils	**Oils**	0.5739	0.1531	0.1243	0.4779
Fats	**Fats**	1.2046	0.0614	0.0499	0.3833
Sugar	**Sugar**	0.0800	-	-	0.1710

[1] Includes electricity used for cooking, refrigeration, and microwave and dishwasher use. It was assumed that Nuts and seeds, Pulses, Oils, and Sugar do not require refrigeration. Refrigeration was used for frozen grain products.

[2] It was assumed that fruits, green vegetables, Nuts and seeds, Dairy, Soymilk, and Sugar do not require cooking

DRF for seafood was derived in terms of Omega-3 fatty acids consumption. Therefore, estimation of consumption related changes to human health required estimating average Omega-3 content of the seafood. Average Omega-3 fatty acid content of 0.0029g Omega-3/g seafood used for this conversion was calculated as a sum of ALA, EPA and DHA fatty acids (‘Fish NS as to type, raw, WWEIA category number 2402, USDA FDC ID: 1098741’) (USDA-Agricultural Research Services, 2019). Similarly, average of polyunsaturated fatty acids and trans fatty acids content in various oils was used to estimate the impact of changes to oil and fat consumption. While estimating consumption related health impact for food groups such as beef and pork, an average of DRFs of red and processed meat was used. While in absence of DRFs for poultry and eggs these food groups were assumed to have no impact on human health. This was justified as most systematic reviews did not find any association between poultry and eggs and the risk of diseases such as T2D, CHD, breast cancer, (Al-Shaar et al., 2020; Bechthold et al., 2019; Feskens et al., 2013; Kazemi et al., 2021; Key et al., 2019; Schwingshackl et al., 2017; Vieira et al., 2017), except Yip et al. (2018), who found a negative association between poultry intake and all-cause and cancer mortalities. The impact of replacing whole grains for refined grains in the RDPs was captured through health benefits offered by whole grains (DRF of -0.34 µDALYs/g. Because of nutritional similarities between milk and milk alternatives (soymilk) DRF of milk was used for soymilk as well. The total health impact of RDP was estimated as a sum of all positive and negative health impacts of individual food subgroups.

3.2.5 Uncertainty Analysis

Uncertainty analysis was conducted using 1000 Monte Carlo Simulations (MCS) in SimaPro to capture the uncertainty in data and to gain confidence in the results. In I/O model uncertainty characteristics provided in the CEDA database were used. Qualitative uncertainty in the CEDA database were translated into a pedigree matrix by assigning an indicator score of 1 for low uncertainty, 2 for medium uncertainty, and 3 for high uncertainty. Indicator scores used for other metrics were 1 for Completeness, 5 for Temporal Correlation, 1 for Geographical Correlation, 4 for Further Technological Correlation, and a default value of 5 for Sample Size. A lognormal distribution was defined in the SimaPro where monetary flows in the I/O model were converted to physical flows using geometric standard deviation estimates of price data. This allowed to capture the uncertainty and variability in retail and producer prices. An assumption was made that the uncertainty and variability in retail process propagated to producer prices. Pedigree matrix was used to define the uncertainty for all retail and consumer LCI, except for the transportation from processor to retail and dishwasher water consumption at consumer. A normal distribution was defined for transportation between processor and retail based on data in CFS (Bureau of Transportation Statistics, 2018), while geometric standard deviation was determined from dishwasher water consumption data (ENERGY STAR, 2021) to define normal and lognormal distributions, respectively.

Statistical significance in mean impact category scores of CDP and RDP was tested with pair-wise bootstrap hypothesis testing method (Neave and Granger, 1968). For each impact category a subsample of 100 impact category scores was randomly selected, with replacement, out of 1000 MCS for both CDP and RDPs. This procedure was repeated to generate 100 such subsamples. A one-tail paired t-test was performed for each subsample to identify statistically significant differences between CDP and each of the RDPs. The difference in means was considered statistically significant if the 95th percentile of p-value distribution was less than or equal to $\alpha=0.05$.

3.2.5 Comparison of pulses with other sources of protein

One of the objectives of the study was to determine the contribution of pulses in environmental and human health benefits that RDPs may offer. Because pulses are rich in protein, their nutritional quality and environmental impact was compared primarily with other foods from protein food group. Nutritional quality of pulses was compared using Nutrient-Rich Food (NRF) index, specifically, NRF9.3 (Fulgoni et al., 2009). NRF9.3 compares foods based on nutrient density (per 100 kcal) for 9 nutrients that are encouraged to consume and 3 nutrients that are advised to limit in the diet. The nutrients that are encouraged include protein, fiber, vitamins A, C, and E, and calcium, iron, magnesium, and potassium, while those advised to limit are saturated fat, added sugar, and sodium. Data on nutrient density for protein foods was obtained from FoodData Central (USDA-Agricultural Research Services, 2019). For fair comparison all preparations of foods and recipes where sodium is added were excluded from the study. NRF9.3 for all foods was calculated for food in their raw form. For meats NRF9.3 was estimated for lean meats only. Environmental impact of these foods was estimated for 100 g serving of protein at the consumer.

3.3. Results

Environmental impacts of RDPs were compared with the baseline CDPs, formulated for females and males separately. The FU for the study was isocaloric diets providing approximately 1800 kcal/person/day to females and 2400 kcal/person/day to males. Environmental impacts were quantified primarily in terms of GWP. However, other impact categories relevant to food systems (LU, FE, ME) and human health impact estimation (PM, Ozone-HH, IR, SOD, HCTox, HNCTox, WC) were included in the study as well. Human health impact was estimated using DALYs, however, for convenience the results were presented in μDALYs. From here on names of all diets are subscripted, when necessary, with 'F' and 'M' to indicate dietary patterns for females and males, respectively. For example, current diets pattern for female is referred as CDP_F, while current dietary pattern for males is referred as CDP_M in the text. Similarly, HealthyUS diet for females and males are referred to as $HealthyUS_F$ and $HealthyUS_M$, respectively.

3.3.1 Environmental Impacts

GWP of diets for FU ranged between 7.89 and 11.69 kg CO_2e for female and between 10.21 and 15 kg CO_2e for male dietary patterns (Figure 3.1). CDPs resulted in the GWP of 8.89 and 11.98 kg CO_2e for females and males, respectively. The GWP increased to 11.69 kg CO_2e for HealthyUS_F and to 15 kg CO_2e for HealthyUS_M. Among the two vegetarian diets analyzed Veg2015 had marginally lower GWP than Veg2010 for dietary patterns for both female and male. However, GWP of both Veg2015 and Veg2010 was greater than the CDP for respective sexes. Lowest GWP among all dietary patterns was observed for Vegan2010, with estimated GWP of 7.89 kg CO_2e for Vegan2010_F and 10.21 kg CO_2e for Vegan2010_M. More than 80% of GWP for CDPs originated from consumption of fruits, vegetables, grains, beef, poultry, dairy, and fats. Top five contributors for CDP were dairy (female- 17%, male- 16%), fruits (female- 13%, male- 10%), beef (female- 13%, male- 17%), refined grains (female- 12%, male- 13%), and vegetables (female- 11%, male- 9%). Together these five food subgroups accounted for 66% and 65% of total GWP of CDP_F and CDP_M, respectively. Contribution from these food groups changed with the diets. HealthyUS diet recommended increasing the consumption of milk, fruits, and vegetables, and replacing some of the refined grains with whole grains. This increased the contribution of dairy to 27% for HealthyUS_F and to 22% for HealthyUS_M. A tradeoff between the contribution of refined and whole grains was also observed for HealthyUS diet, where partial substitution of refined grains with whole grains increased the contribution of whole grains. Contribution of beef, fruits, and vegetables only changed by about 1% for HealthyUS_F. Approximately 3% decrease in the contribution of Beef to HealthyUS_M was negated by increase in the contribution of fruits (up by 4%) and vegetables (up by 3%). This resulted in increasing the contribution from these top five groups to 74% and 71% for HealthyUS$_F$ and HealthyUS$_M$, respectively.

For other food subgroups absolute contribution from dairy, fruits, vegetables, whole grains, and refined grains remained at the level observed for HealthyUS diets. This was because recommended consumption of these food subgroups was same for all RDPs. Substitution of meat, poultry, and seafood with nuts and seeds, tofu, and pulses in Veg2015 and Veg2010 increased the contribution from plant-based sources of protein. While, omitting beef, poultry, and seafood eliminated their contribution to GWP, total increased contribution from other food groups was large enough to increase the total GWP of these diets. For example, compared to the

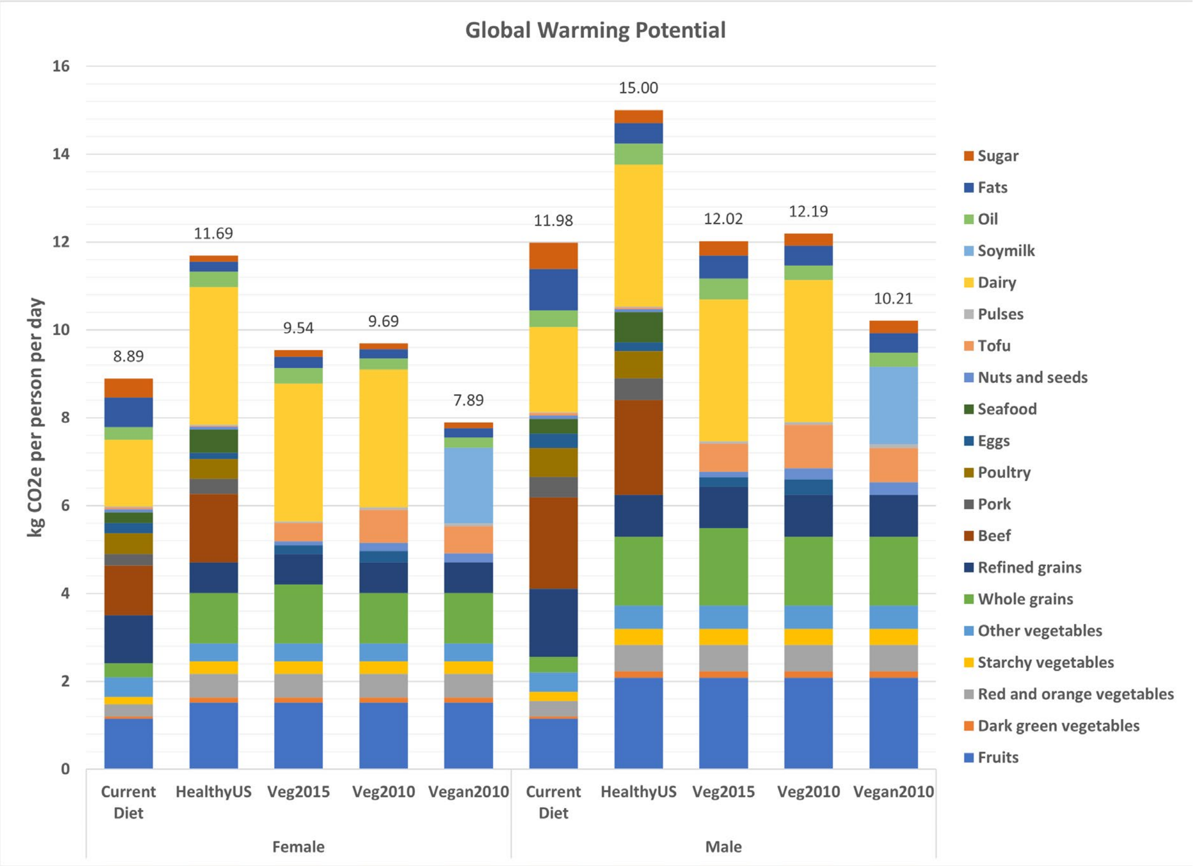


Figure 3.1- Global warming potential of current and recommended dietary patterns showing contribution from food subgroups

CDP$_F$ elimination of beef, pork, poultry, and seafood and decreasing the consumption of fats and sugar decreased the contribution from these foods by 3.28 kg CO$_2$e for Veg2015$_F$. However, increased consumption of other food subgroups increased the GWP by 3.93 kg CO$_2$e, resulting in net increase in GWP of Veg2015$_F$ by 0.65 kg CO$_2$e as compared to CDP$_F$ (Figure 3.2). Dairy and whole grains, whose contribution increased by 1.62 and 1.02 kg CO$_2$e, respectively, were primarily responsible for this net increase in GWP. Other food subgroups with large increase in GWP compared to CDP$_F$ were fruits, vegetables, and tofu. Contribution of nuts and seeds, pulses, and oil increased only by 0.03, 0.02, and 0.07 kg CO$_2$e compared to CDP$_F$. For Veg2010$_F$ recommended increased consumption of eggs, nuts and seeds, and tofu compared to Veg2015$_F$ further increased the GWP of Veg2010$_F$. For similar reasons the GWP of Veg2015$_M$ and

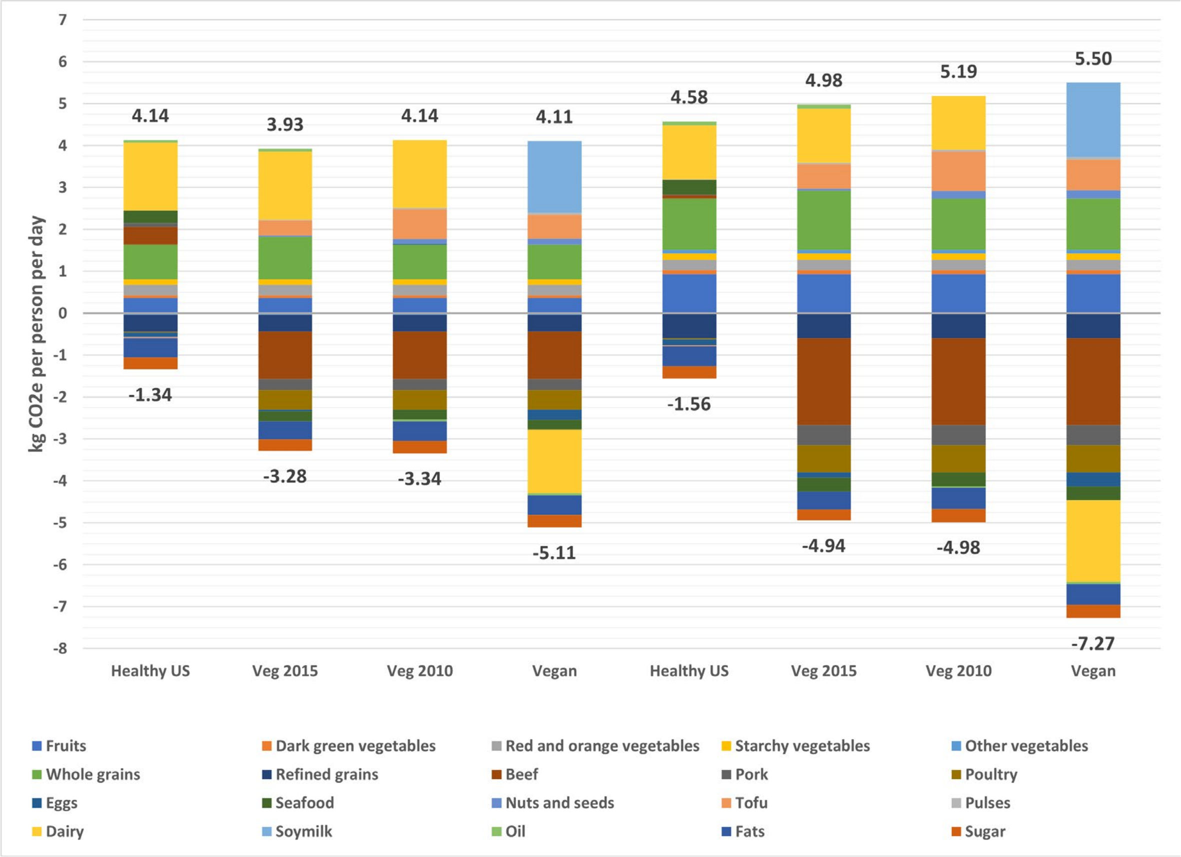


Figure 3.2- Changes to the contribution from food subgroups to the GWP associated with changes to the amounts in RDPs compared to CDPs.

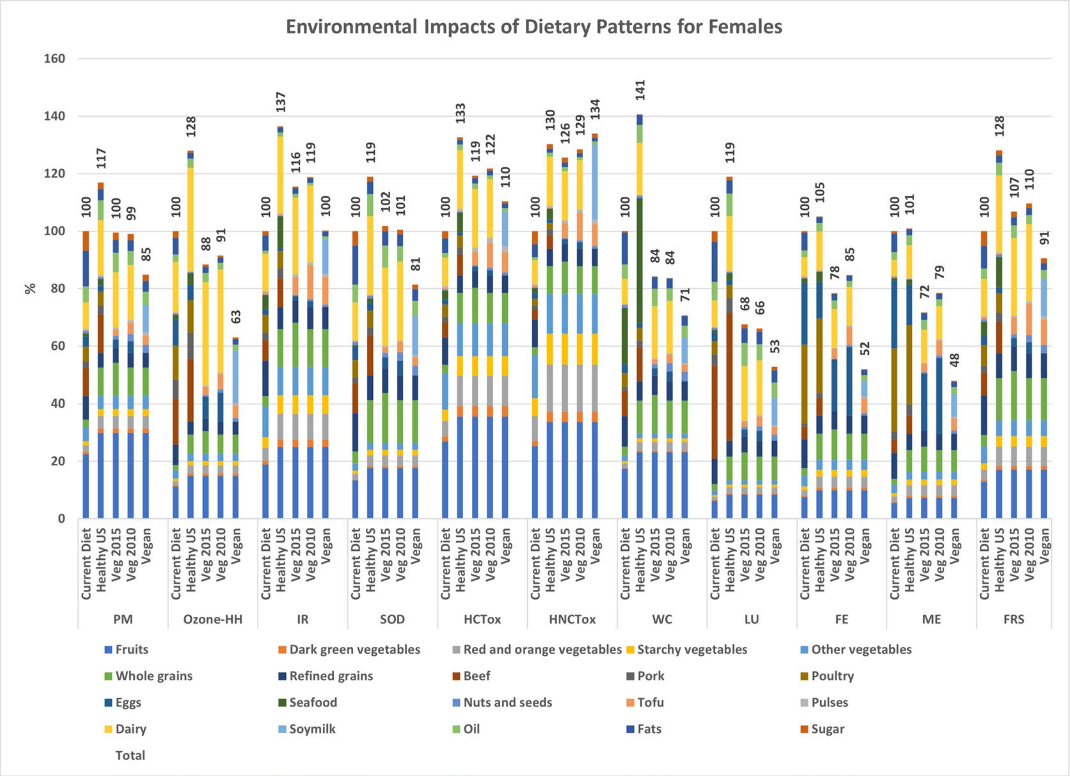
Veg2010_M was greater than CDP_M. However, the difference between these RDPs for male and CDP_M was lower than that for females. This was attributed to the differences in recommended changes to the diet between females and males. Compared to Veg2015_F and Veg2010_F greater reductions in the consumption of beef, pork, poultry, and seafood were recommended for Veg2015_M and Veg2010_M, respectively. Moreover, recommended increase in the consumption of dairy was lower for Veg2015_M and Veg2010_M compared to their counterparts for females. These factors, in addition to the changes to GWP of other dietary food subgroups, resulted in only modest comparative increase in the GWP of Veg2015_M and Veg2010_M.

Both Vegan2010_F and Vegan2010_M resulted in the lowest GWP compared to any other sex-specific dietary patterns, including CDPs. This was primarily because food subgroups such as beef, pork, and dairy are excluded from the diet. Exclusion of these food subgroups of animal origin decreased the total GWP by 4.11 kg CO_2e and 5.50 kg CO_2e for Vegan2010_F and Vegan2010_M, respectively compared to the CDPs. This change was large enough to reduce the total GWP of Vegan2010_F and Vegan2010_M by 1 kg CO_2e and 1.77 kg CO_2e, respectively (Figure 2), even though increasing the consumption of fruits, vegetables, whole grains, soymilk, and other plant-based food groups increased their contribution to GWP. The largest contributors to Vegan2010_F diets were soymilk (22%), fruits (19%), vegetables (14%), whole grains (14%) and refined grains (9%), which were responsible for 81% of total GWP. The same five food subgroups were responsible for 79% of total GWP of Vegan2010_M as well. However, their contributions were different. Fruits were the largest contributor to the Vegan2010_M and accounted for 20% of GWP, followed by soymilk (17%), vegetables (16%), whole grains (15%), and refined grains (9%).

Overall, all dietary patterns formulated for male had greater GWP compared to the respective diets for females, which demonstrates the impact of caloric content of diets on GWP. Dietary patterns for males were formulated to deliver 2400 kcal/person/day, requiring more quantity from each food subgroups than the diets for females, which delivered only 1800 kcals/person/day. Additionally, relative contribution from each food groups also differed between equivalent dietary patters for male and female. For example, dairy contributed 27% of total GWP of $\text{HealthyUS}_\text{F}$ and only 22% for $\text{HealthyUS}_\text{M}$, when $\text{HealthyUS}_\text{M}$ included 13 g more milk. This was attributed to the differences in nutritional requirements of both sexes, which resulted in differences in proportions of each food subgroup in the diet. Dairy constituted 29% and 24% of total diet in $\text{HealthyUS}_\text{F}$ and $\text{HealthyUS}_\text{M}$, respectively, resulting in greater contribution from dairy to the GWP of $\text{HealthyUS}_\text{F}$.

Other environmental impacts of the RDPs are presented in Figure 3.3 in comparison to the CDP. Environmental impact score of CPD is set to 100% for each impact category. The figure also shows relative contribution of each food group to the environmental impact of the diet. HealthyUS diets had the largest environmental impact across all categories for both female and male diets, primarily because of recommended increase in the consumption of fruits, vegetables, whole grains, and dairy in addition to the retained consumption of animal-based protein and seafood. Seafood dominated WC for both CDP and HealthyUS contributing 20% and 30%, respectively to the dietary patterns. Beef dominated the impact for all other categories, excluding HCTox and HNCTox, to which fruits contributed to the most. Impact of beef and dairy was noticeable for LU.

Environmental impact Veg2015 and Veg2010 was greater than CDP for IR, SOD, HCTox, and HNCTox for both female and male diets. This could be associated with increased use of chemicals in the production of fruits, vegetables, grains, and feed in dairy productions (HCTox and HNCTox) as well as increased use and disposal of packaging material (HCTox), increased requirement for refrigeration (SOD), and increased fossil fuel consumption (IR) as can be seen for FRS. Because of the small difference, the particulate matter emissions both Veg2015 and Veg2010 could be considered comparable to the CDP. Higher HCTox and HNCTox impact of Vegan 2010 could also be linked to the increased use of plant protection chemical used in the production of plant-based foods. Large contributors to most of these impact categories were primarily beef, dairy, fruits, and soymilk (only in Vegan2010). For few impact categories the contribution from dairy almost doubled for HealthyUS, Veg2015, and Veg2010. Absence of beef, pork, poultry, and seafood helped reduce the WC, LU, FE, and ME in both Veg2015 and Veg2010 diets. Food subgroups that dominated these impact categories were fruits (WC), dairy (LU), and eggs (FE and ME). Substituting dairy with soymilk and eggs with other plant-based protein foods in Vegan2010 further decreased the impact for these categories. Except for HCTox and HNCTox, Vegan2010 also had the lowest impact for all remaining categories.



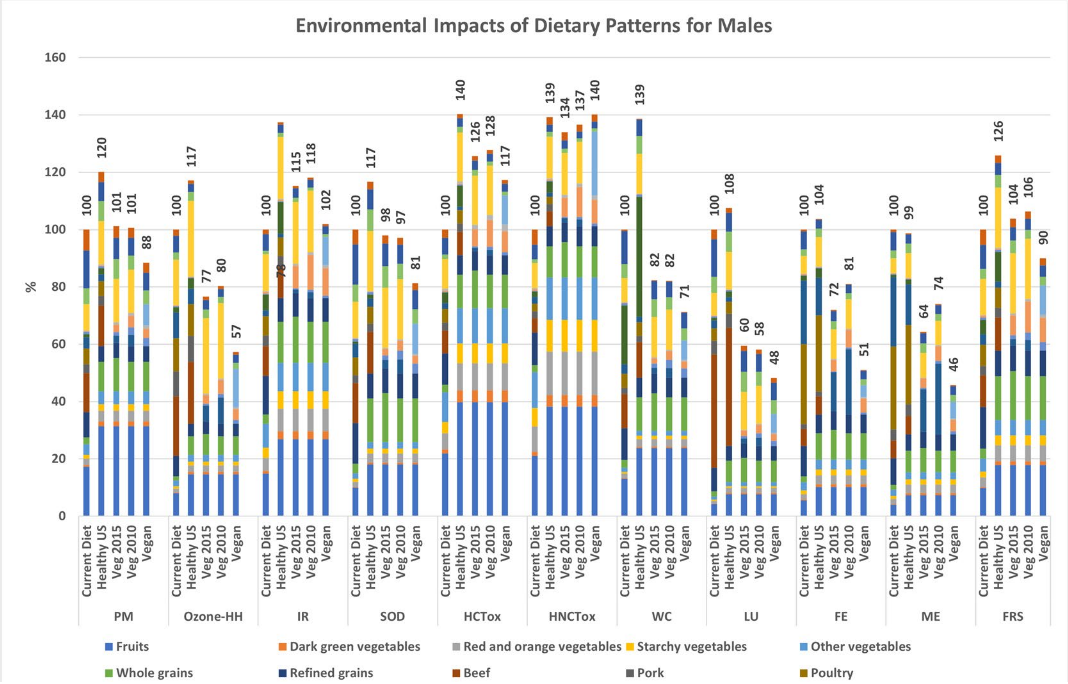


Figure 3.3- Midpoint impacts of current and recommended dietary patterns for impact categories important for environmental sustainability and human health. Because of the differences in units the results are presented as percentage difference between RDPs and CDPs.

3.3.2 Human Health Impact

Human health impact of dietary patterns was measured as emission related impact (HH_E) that negatively affects human health and benefits received from consuming RDPs that affects health positively (HH_D). HH_E for the current diets was 48.28 µDALYs for CDP_F and 63.23 µDALYs for CDP_M (Figure 3.4). A trend similar to the GWP was observed, where HealthyUS, Veg2015, and Veg2010 had greater HH_E compared to the CDPs. However, the magnitude of change between these diets and the CDP was smaller. For example, GWP of $HealthyUS_F$ was 32% greater than then CDP_F, while it was only 23% for HH_E. Similarly, HH_E of $Veg2010_M$ was only 0.01% greater than the CDP_M compared to its GWP, which increased by 2.36%. This resulted from the differences in of magnitude and directional change in the midpoint impacts of these diets and characterization factors (CF) used in ReCiPe 2016 to estimate human health (endpoint) impact from the environmental (midpoint) impacts. Vegan2010 had the lowest HH_E among all dietary patterns. Impact on human health from particulate matter emissions dominated HH_E of diets. Other midpoint categories with large contribution to the HH_E were GWP, WC, and HNCTox (Fig B.1). These midpoint impact categories were responsible for between 98% to 99% of total HH_E. Environmental impact of fruits, dairy, vegetables, beef, and grains contributed the most towards HH_E, contributing between 63% and 81% of total endpoint impact (Figure 3.5). Between 16 and 31% of HH_E originating from fruits, making it the largest contributor. This large contribution from fruits could be associated with greater PM and HNCTox impact observed for midpoint impact categories.

The results for HH_D and net human health impact of dietary patterns HH_{Net} are presented in Figure 2.5. HH_{Net} was estimated as a difference between the HH_E and HH_D. All RDPs were estimated to offer health benefits and decrease the global burden of diseases. Negative numbers

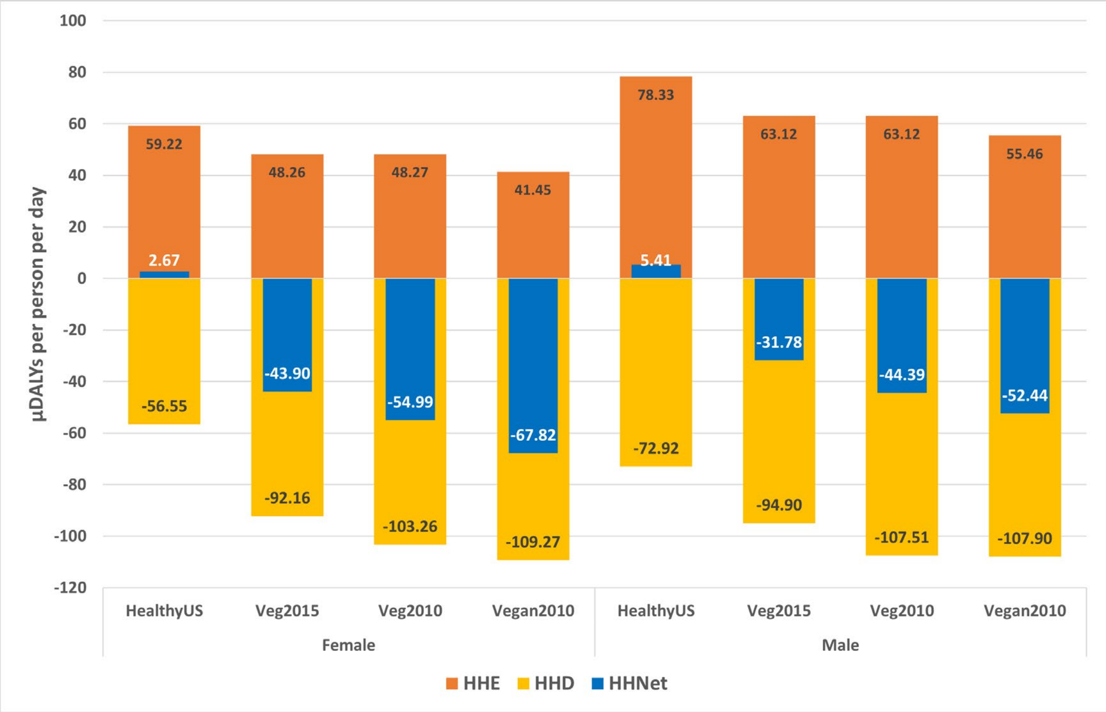


Figure 3.4- Human health impact of dietary patterns measured in terms of µDALYs/person/day. The CDPs are assumed to be responsible current individual burden of diseases.

in the figure indicate reduction in the burden of diseases or health benefits. HH$_D$ for the RDPs ranged between -55.97 µDALYs for HealthyUS$_F$ and -108.41 µDALYs/day for Vegan2010$_M$. However, a trend existed for both female and male RDPs where the health benefits were highest for Vegan2010, followed by Veg2010, Veg2015, and HealthyUS. Increasing the consumption of whole grains showed the greatest potential for protection against diet related burden of disease with HH$_D$ ranging between -35.39 and -44.95 µDALYs/day. Nut and seed consumption also offered substantial health benefits, especially for Veg2010 and Vegan2010 (range: -21.75 to -30.12 µDALYs/day). Another cause of potential decreased burden of diseases was benefits offered by increased consumption of fruits and vegetables and decreased consumption or elimination of beef and pork. HealthyUS diet recommended marginally increasing beef and pork consumption and decreasing the consumption of nuts and seeds. This increased HH$_D$ by 8.85

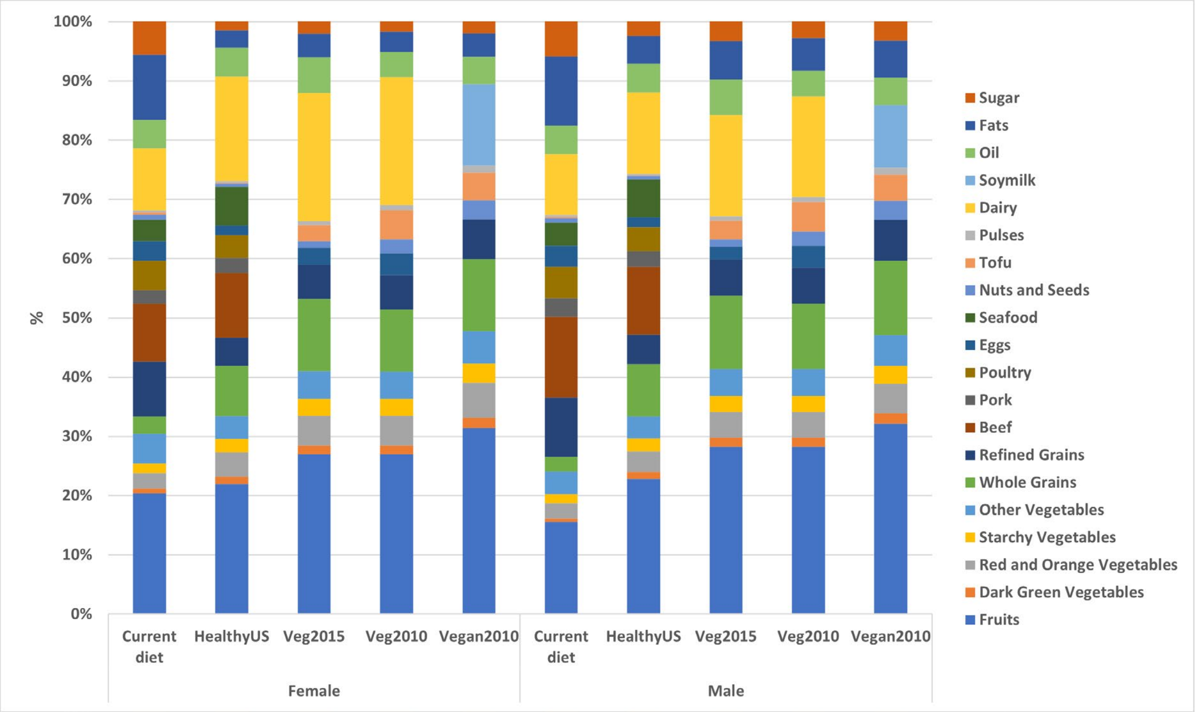


Figure 3.5- Contribution of food subgroups to emission related human health impact

μDALYs/day for HealthyUS$_F$ and by 2.50 μDALYs/day for HealthyUS$_M$. Similarly, eliminating seafood from the diet also eliminated the protection Omega-3 fatty acids offer thereby, increasing HH$_D$ of vegetarian and vegan diets by 3.41 μDALYs/day and 4.77 μDALYs/day for females and males, respectively. However, this was offset by protection offered by other food subgroups in these dietary patterns. While all RDPs offered potential health benefits, when both HH$_E$ and HH$_D$ were accounted for HealthyUS diets resulted in net increase in the burden disease. HH$_{Net}$ for HealthyUS$_F$ and HealthyUS$_M$ was 3.26 and 6.26 μDALYs/day, respectively. Essentially, any health benefits offered of HealthyUS diet were offset by their impact on human health associated with cradle-to-grave supply chain emissions. On the other hand, Veg2015, Veg2010, and Vegan2010 offered net protection or reduction in burden of diseases. This ranged between -30.92 μDALYs/day for Veg2015$_M$ and -68.28 μDALYs/day for Vegan2010$_F$. Although dietary patterns for males offered greater reduction in burden of disease (HH_D: -72.06 to -108.41 μDALYs/day for male; HH_D: -55.97 to 109.73 μDALYs/day for females), their HH_E was greater compared to the counterpart diets for females. For this reason, HH_{Net} was greater for RDP_F compared to RDP_M.

3.3.3 Contribution of Pulses

Contribution of pulses to HH_D was relatively smaller compared to other food groups such as whole grains and especially for HealthyUS diet that relied primarily on animal proteins. However, for vegetarian and vegan diets HH_D ranged between -3.12 μDALYs/day ($Veg2015_F$) and -9.15 μDALYs/day ($Vegan2010_M$) with vegan diets offering most benefits from the consumption of pulses. The DRF for pulses was -0.23 μDALYs/g, which was greater than fruits and vegetables. However, recommended increase for pulses ranged between 0.4 to 26.7 g for females and 4 to 40 g for males as opposed to 64 to 163 g recommended increase for fruits. For this reason, estimated health benefits offered by pulses were lower than few other food subgroups (fruits, vegetables, whole grains). Pulses were the largest source of protein in Veg2015 and Vegan2010 and the second largest in Veg2010 and provided between 29% and 42% of total protein females and between 30% and 41% of total protein in RDPs for males. While the CDPs and HealthyUS diets relied primarily on animal-based protein, pulses still provided 8% to 10% of total dietary protein, largest among the plant-based sources of protein. The GWP contribution of pulses to the GWP of the dietary patterns was less than 1%. Even for the $Vegan2010_F$ and $Vegan2010_M$ that depended on pulses as a primary source of protein, the GWP contribution was only 0.06 and 0.09 kg CO_2e, approximately 0.79 and 0.84% of total dietary GWP, respectively. The largest contribution from pulses to other midpoint impact

Table 3.5- Cradle-to-grave GWP of sources of protein for 100 g of protein consumed and their NRF9.3 nutritional density score

Food Subgroup	NRF9.3	GWP kg CO_2e
Beef	45	19.68
Pork	53	6.86
Poultry	49	5.62
Eggs	29	7.43
Seafood	47	7.45
Nuts and seeds	27	3.91
Tofu	53	2.94
Pulses	57	0.50

categories was 1.39% for PM, 1.04% for Ozone-HH, 1.18% for IR, 0.81% for SOD, 2% for HCTox, 1.12% for HNCTox, 0.69% for WC, 0.87% for LU, 0.98% for FE, 0.82% for ME, and 1.14% for FRS. Because of this low environmental impact, the endpoint impact of pulses was low as well, ranging between 0.27% and 1.18% for RDP_F and between 0.28% and 1.21% for RDP_M. Moreover, for 100 g protein at the consumer the GWP of pulses was 0.5 kg CO_2e, lowest among all sources of protein used in the study. Comparatively, GWP of other plant-based and animal-based protein sources was at least 5 and 11 times greater (Table 3.5). Pulses as a food subgroup was nutritionally superior compared to other protein sources as well. An average NRF9.3 index for pulses was 57, at least 4 points higher than both plant and animal-based protein sources (Table 3.5). However, NRF9.3 score of pulses varied by the pulse species and variety, and it ranged between 39 for chickpea and 67 for pinto beans and pigeon pea (red gram). This difference was driven by the dissimilarities in nutritional profile of pulses used for this analysis (black bean, pinto bean, chickpea, lentil, and pigeon pea). Black bean, pinto bean, and pigeon pea contain at least twice as much potassium and calcium as chickpea and lentil. Moreover, chickpea contains at least four times more natural sugar than other pulse species. Influence of these factors decreased the NRF9.3 score of chickpea and lentil.

3.3.4 Uncertainty Analysis

Results of uncertainty analysis performed using 1000 MCS are presented in Figure 3.6 with box and whisker plot. The boxes in this plot represent 25th, 50th, and 75th percentile, while the error bars (whiskers) represent 5th and 95th percentile of the impact category distribution. The statistical analysis indicated that the difference between mean GWP of HealthyUS and CDP was statistically significant with $p<0.05$. Similarly, lower GWP of Vegan2010 diet was also confirmed by the statistical analysis ($p<0.05$). For vegetarian diets, their greater GWP was statistically significant only for Veg2010$_F$ ($p<0.05$). Based on the statistical analysis and the results of MCS, the GWP of Veg2015$_F$, Veg2015$_M$, and Veg2010$_M$ can be considered similar to CDP ($p>0.05$).

The statistical analysis also indicated that HealthyUS$_M$ had greater environmental impact for all impact categories included in the study ($p<0.05$). Greater environmental impact all HealthyUS$_F$ was found statistically significant for all impact categories except ME. Similarly, lower environmental impact of Vegan2010 diet for PM, Ozone-HH, SOD, WC, LU, FE, ME, and FRS were also found to be statistically significant ($p<0.05$) for both sexes. Contrarily, its impact on IR, HCTox, and HNCtox were similar to CDP ($p>0.05$). For Veg2015, statistically significant differences with respect to CDP were found only for FRS (Veg2015$_F$ > CDP), FE (Veg2015$_F$ and Veg2015$_M$ > CDP), LU (Veg2015$_F$ and Veg2015$_M$ < CDP), ME (Veg2015$_F$ > CDP, Veg2015$_M$ < CDP), and Ozone-HH (Veg2015$_M$ < CDP). Similarly, for Veg2010 diet, greater impact in terms of PM (Veg2010$_M$), HNCTox (Veg2010$_M$), FRS (Veg2010$_F$ and Veg2010$_M$); and lower impact in terms of Ozone-HH (Veg2010$_M$), LU (Veg2010$_F$ and

Veg2010$_M$), FE (Veg2010$_F$ and Veg2010$_M$), ME (Veg2010$_F$ and Veg2010$_M$) were also found statistically significant.

Emission related human health impact of Veg2015 and Veg2010 were comparable to the CDPs, while greater HH$_E$ of HealthyUS and lower HH$_E$ of Vegan2010 were confirmed by the uncertainty analysis. However, when the combined effect of both HH$_E$ and HH$_D$ was considered, the uncertainty analysis indicated that any health benefits offered by HealthyUS diet were negated by detrimental impact caused to human health by cradle-to-grave emissions (Figure 3.4). This interpretation relies on the assumption that HH$_{Net}$ of CDPs is responsible for the current individual burden of diseases and therefore, represent median HH$_{Net}$ of zero on the plot. It was also confirmed that despite comparable HH$_E$, Veg2015 and Veg2010 offer net health benefits

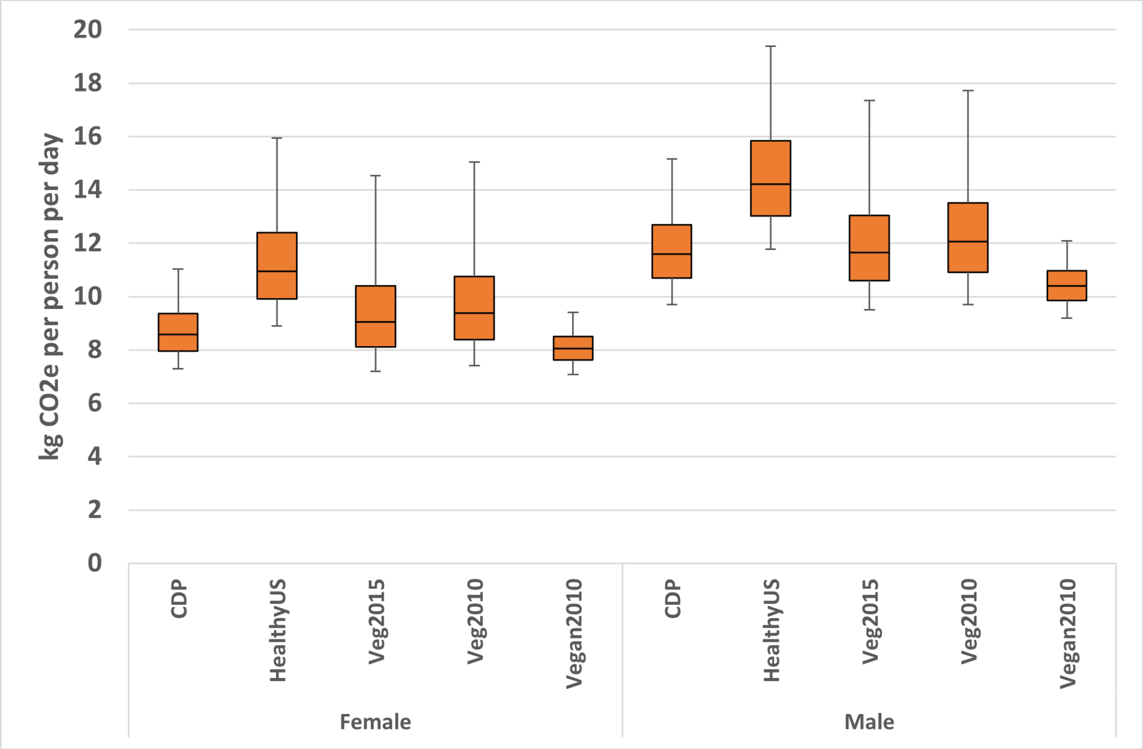


Figure 3.6- Results of uncertainty analysis for GWP presented on Box and Whisker plot. The Box represents 25th, 50th, and 75th percentile (bottom to top), while whiskers represent 5th and 95th percentile of the distribution.

and can help in reducing the individual's burden of disease. Vegan2010 showed the greatest potential for health benefit compared to all other RDPs.

3.4. Discussion

3.4.1 Environmental and health impact

Based on comparative and uncertainty analysis it can be stated that switching to HealthyUS diet can increase a person's food related GWP. Uncertainty analysis also confirmed increased impact category scores for HealthyUS diet for PM, Ozone-HH, SOD, HCTox, WC, LU (only for HealthyUS_F), and FRS (Figure B.2). Moreover, HH_{Net} of HealthyUS diet was similar to the CDP. It must be noted that the dietary pattern itself is healthier compared to the current dietary patterns for both sexes. Recommended dietary changes could decrease individual burden of diseases by 55.97 μDALYs/day (95% CI: ± 0.3 μDALYs/day) for HealthyUS_F and by 72.06 μDALYs/day (95% CI: 0.32 μDALYs/day) for HealthyUS_M. However, these benefits are negated by increased emissions and water consumption from the cradle-to-grave activities, which negatively impact human health. Large scale adoption of this dietary pattern can further exacerbate the effects and magnitude of climate change, resource scarcity, and environmental degradation. Therefore, HealthyUS diet can be considered environmentally less sustainable than the current dietary patterns, while offering no net benefits to the human health.

While comparative analysis indicated greater GWP for Veg2015 and Veg2010 diets, it can be considered comparable to the CDP for both sexes based on the uncertainty analysis. These diets also had lower Ozone-HH, LU, FE, and ME than CDP, but PM, IR, SOD, HCTox, HNCTox, and WC comparable to the CDP (Figure B.2). Moreover, these diets also offered net benefits to human health showing a potential to reduce individual burden of disease by 91.58 μDALYs/day (95% CI: 0.4 μDALYs/day), 103.59 μDALYs/day (95% CI: 0.43 μDALYs/day), 94.04 μDALYs/day (95% CI: 0.4 μDALYs/day), and 107.88 μDALYs/day (95% CI: 0.45 μDALYs/day) for Veg2015$_F$, Veg2010$_F$, Veg2015$_M$, and Veg2010$_M$, respectively. Therefore, these dietary patterns can an option to improve human health. However, they might not completely decrease the environmental impact of food systems. Even though the GWP, HCTox, HNCTox, and FRS of these diets are statistically comparable to the CDP, substantial number of MCS runs resulted in higher impact score for Veg2015 and Veg2010. For example, 100% of MCS runs for HCTox and HNCTox and at least 68% MCS runs for FRS indicated that Veg2015 and Veg2010 diets had higher impact than CDP. Some of these differences in impact category scores were small enough to render the distribution of results statistically non-significant. However, the study underscored the need to decrease the environmental impact of all food commodities in addition to meat. Between 62% and 67% of total GWP in these two dietary patterns originated from plant-based foods, while dairy, eggs, and fat were responsible for the rest.

Only Vegan2010 demonstrated a potential to reduce the GWP, PM, Ozone-HH, SOD, WC, LU, FE, ME, and FRS of the food systems, while offering maximum net benefits to the human health. The HH$_{Net}$ for Vegan2010 was 109.73 μDALYs/day (95% CI: 0.47 μDALYs/day) and 108.41 μDALYs/day (95% CI: 0.47 μDALYs/day) for females and males, respectively. However, the IR, HCTox, and HNCTox impact of these dietary patterns was comparable to the CDP. Similar to Veg2015 and Veg2010, 100% of MCS runs resulted in greater HCTox and HNCTox impact for both Vegan2010$_F$ and Vegan2010$_{M.}$ But the overlap of distributions with the CDP$_F$ and CDP$_M$, respectively indicated that these differences were statistically non-significant. However, it must be noted that toxicity characterization factors contain well-documented uncertainties and therefore, further investigation into HCTox and HNCTox may be necessary.

Nonetheless, results for HCTox and HNCTox highlighted the issues with use of chemicals in the agricultural system, especially, in plant-based commodities, as well as with the release and fate of chemicals and heavy metals from coal mining activities and waste treatment. In Vegan2010$_F$, for example, fruits and vegetables accounted for 63% of total HCTox impact. Activities related to coal mining, farming, and waste treatment were responsible for 83% of total HCTox of Vegan2010$_F$ diet. When animal-based food subgroups were included in the diet (CDP$_F$), the contribution from individual food subgroups varied but fruits and vegetables remained the largest contributors to HCTox (50% of total HCTox impact for CDP$_F$). Similar results were also observed for HNCTox.

Based on these results adoption of Vegan2010 would be an ideal option to simultaneously lower environmental impacts of the food systems and improve human health through lower emissions and decreased burden of diseases. Veg2015 and Veg2010 would be the next best option to lower the burden of diseases, but the environmental benefits would be limited to lowering Ozone-HH, LU, FE, and ME. Some of the other important environmental issues such as GWP would remain unchanged at best and increase at worst. However, these environmental impacts could be lowered through changes to the consumer behavior. Because dairy is the largest contributor to Veg2015 and Veg2010, partial replacement of dairy with dairy substitutes could potentially decrease the diet related GWP. Our analysis (not shown here) suggests that replacing 50% of all dairy with soymilk could decrease the GWP of Veg2015$_F$ and Veg2015$_M$ by 1.2% and 6.5%, respectively compared to respective CDPs. While this may seem a small change, particularly for Veg2015$_F$, it was 8% lower than the average GWP of Veg2015$_F$ that only included dairy (Section 3.1). Reducing food waste could be another possibility to decrease the GWP. Total estimated losses in the study between processor (primary weight) and loss adjusted weight at consumer (actual consumption) ranged between 15% and 64%, with pulses resulting in least amount of losses and food subgroup 'Other Vegetables' resulting in the most. The average of food losses for all food groups was 41%. Some of the losses at the processor are necessary in order to convert a commodity from fresh product to retail-ready product (e.g., live chicken to boneless meat), and may not be avoided. However, these food losses are usually utilized in manufacturing of other products such as pet food and only small percentage ends up in waste treatment plant. Loss of non-edible portion of food such as cores of fruits cannot be avoided either by a consumer. However, loss at retail and plate waste could be avoided through changes in consumer behavior. These losses affect the overall environmental impact of food system in two ways. Lost food at the retail and consumer level is mostly sent to the landfill, where the aerobic or anaerobic digestion emits GHG emissions. Birney et al. (2017) reported that 95% of food waste at the consumer either ends up in landfill or combustion facility, resulting in per capital GHG emissions of 132 kg CO_2e. In the present study emissions from landfill accounted for 5.9% to 8.3% of total GHG emissions for individual dietary pattern. The contribution was generally higher for RDPs compared to CDPs showing the increased food waste from the RDPs. For few food subgroups such as fruits and vegetables emissions from the landfill resulting from food loss was the largest contributor to the GHG emissions of individual food commodity with as much as 58% of waste-related emissions originating from the consumer level (dark green vegetables). The second pathway in which the food loss affects the GWP of the food system is through increased production at the primary level to compensate for the losses and meet the consumer demand. If these losses could be minimized the GWP of food systems could be decreased. In an ideal scenario where all consumer losses were avoided, the GWP of diets decreased by 27% to 30%. While avoided all food losses at the consumer is not practical, this shows the importance of reducing food waste throughout the food supply chain. Moreover, reducing losses and consequently, environmental impacts can also help reduce the emission related negative impacts on human health while maintaining the benefits of consuming healthier diets. As a result, individual burden of disease can be reduced even more through consumption of RDPs.

3.4.2 Comparison with other studies

The system boundary of most other studies that evaluated the environmental impact of U.S. diets ended at farm/processor or retail gate. To our understanding, only one study conducted by Kim et al. (2020) has analyzed cradle-to-grave food supply chain. The GWP of current dietary pattern providing 2547 kcal reported by Kim et al. (2020) was 8.8 ton CO_2e per household per year, which is equivalent to 6.8 kg CO_2e/capita/day and 9.1 kg CO_2e/capita/day for 1800 kcal and 2400 kcal diet, respectively, assuming household size of 2.5. GWP of CDP_F and CDP_M was 8.9 and 12.0 kg CO_2e/capita/day, respectively in our study. Kim et al (2020) also estimated lower GWP for vegetarian diet compared to the baseline diet, which was directionally opposite to findings of our study. The difference in the GWP of current diets between two studies resulted from the differences between food commodity sector mapping in CEDA database, disaggregation of these sectors, retail prices and retail to producer price conversion factors used for converting monetary flows in CEDA to physical units, and allocation between primary and secondary (byproduct). While mapping food commodity sectors in the CEDA database we tried to achieve as much granularity as possible. For example, Kim et al. (2020) aggregated cheese; fluid milk; dry, condensed, and evaporated milk; and ice cream and frozen dessert sectors for milk and dairy food group, while yogurt was added in our study. Similarly, we differentiated between whole and refined grains and used mass contribution from bread and bakery manufacturing; frozen specialty food manufacturing; pasta, rice, and crackers manufacturing; breakfast cereals manufacturing; flour milling; and all other food manufacturing (after disaggregating tofu manufacturing) to map grains at the processing gate, while Kim et al. (2020) only used 'Bread and bakery product manufacturing.' Moreover, retail prices in Kim et al. (2020) were estimated from per capita loss-adjusted food availability and food expenditure data, while QFAHPD data adjusted for inflation was used in this study. This resulted in higher retail prices for few sectors such as grains where weighted average retail price for whole and refined grains was \$6.19/kg and \$5.18/kg compared to \$1.82/kg used by Kim et al. (2020). Choice of CEDA economic sector and differences in retail prices also resulted in difference in conversion factors in CEDA used for estimating producer price from the retail price. For example, Kim et al (2020) used retail price for dairy was \$2.27/kg with CEDA price conversion factor of 0.91 (producer's price \$2.06/kg), while the retail price for dairy ranged between \$1.15/kg and \$10.44/kg in this study with CEDA price conversion factors between 0.78 and 0.92. This resulted in weighted average producer's price of \$2.66/kg for dairy in our study. The difference in prices between two studies was prominent for grains, beef, pork, seafood, nuts and seeds, oils, and fats. Because the GWP of 1 kg of food depends on the producer's price in I/O database, higher producer's price results in greater GWP of food at the producer gate. Another difference in methodologies between Kim et al. (2020) and the present study is allocation between products and byproducts at the producer gate. Kim et al (2020) estimated products and by-product fractions in CEDA database using primary loss estimates in the LAFA database. These mass-based food loss estimates were directly applied to monetary flows in CEDA, potentially resulting in over or underestimation of GWP. For example, product and byproduct for dairy sector were estimated using 0.11% primary loss and allocation factors of 81.1% and 12.9%

for product and byproduct, respectively. Because mass-based food loss estimates were applied to monetary flows, \$0.9989 worth of Dairy products in CEDA carried only 81.1% of upstream burdens. Our analysis (not shown here) indicated that at a producer's gate both product and byproduct carry the same burdens per USD earned from their sale and therefore, allocation is not necessary when dealing with monetary flows in I/O database. Moreover, balancing monetary flows of products and byproducts is intrinsic to the construction of I/O database making these allocations at the producer's gate redundant. Therefore, these allocations were avoided in this study. These differences in the methodology may have resulted in greater GWP of diets and directional shift for vegetarian diets observed in this study.

The cradle-to-retail GWP of CDP_F was 8.92 kg CO_2e/capita/day, within the range (5.6 – 10.3 kg CO_2e/capita/day) reported in other studies that used EIO-LCA (Boehm et al., 2018; Canning et al., 2020; Jones and Kammen, 2011; Weber and Matthews, 2008). However, GWP of CDP_M was outside this range, which could be associated with differences in methodologies and I/O databases used in these studies. These studies used Consumer Expenditure Surveys published by U.S. Bureau of Labor Statistics to derive current consumption patterns in the US and did not differentiate between consumption patterns by sexes. Moreover, full cradle-to-retail food system was modeled in EIO-LCA instead of hybrid approach used in this study. However, mean cradle-to-retail GWP of HealthyUS was greater than while that of Veg2015 and Veg2010 diets was lower than the CDP for both female and male dietary patterns which was similar to the trend reported by Hitaj et al. (2019). Likewise, lower cradle-to-processor gate GWP of Veg2015, Veg2010, and Vegan2010 was also similar to the GWP of these diets observed in other studies (Blackstone et al., 2018; Goldstein et al., 2017; Heller and Keoleian, 2015; B. F. Kim et al., 2020; Tilman and Clark, 2014). Some of these studies used process-LCA to estimate the cradle-to-farmgate/processor gate GWP of diets, which explains lower estimates of mean GWP compared to this study. Because EIO-LCA includes both direct and indirect emissions of an economic sector, it results in higher estimates of environmental impact than process-LCA. While LCA studies quantifying the health impacts of diets in terms of DALYs could not be found, Hallstörm et al. (2017) reported reduction in the risk of CHD, CRC, and T2D by 20 – 45% associated with adoption of healthier diets, which is in agreement with the findings of this study.

3.4.3 Limitations

One of the limitations of this study stemmed from the use of academic version of the CEDA database, which was created using 2002 monetary data of the US economy. While we adjusted these data using PPI to represent value of US dollar in 2018, an intrinsic assumption was that the structure of the US economy remained unchanged. Because CEDA is environmentally extended database this assumption also implied that the contribution of various economic sectors to the total environmental impact of the economy did not change either. Moreover, technological advances and system efficiency improvements that could lower the environmental impact of the economy were not captured in the use of academic version of the CEDA database. Similarly, resource use data for the retail sector was dated as well. It is possible that the resource use efficiency has improved in the retail sector since 2011. Because technological advances and resource use efficiency tend to lower the environmental impacts, we predict that the use of older data in the study could lead to overestimation of diet related environmental impacts. The sensitivity analysis also revealed that the environmental impacts of few food groups were extremely sensitive to the retail and consequently producer prices than others. This was especially true for dairy, where changing the prices by 10% changed the GWP by approximately 3%. Despite our best efforts to use accurate price data for all food groups, variability and uncertainty in the data could result in uncertainty in the results. Few assumptions such as using same DRF for all types of vegetables, assuming identical benefits from dairy and soymilk, using average of DRF for red and processed meat, and missing DRF for tofu can affect the estimated health benefits of RDPs as well. These uncertainties were captured in the MCS however, more granular, and current data would help to reduce these uncertainties.

3.5 Conclusion

The GWP of diets in this study ranged between 7.9 to 11.7 kg CO_2e/capita/day for females (1800 kcal diets) and between 10.2 and 15.0 kg CO_2e/capita/day for males (2400 kcal diets). GWP of current dietary patterns was 8. 9 and 12.0 kg CO_2e for CDP_F and CDP_M, respectively. Based on the comparative, uncertainty, and statistical analysis it can be concluded that adopting Vegan2010 dietary pattern can lower the environmental impact of food systems, while HealthyUS will increase it. While vegetarian dietary patterns (Veg2015 and Veg2010) can successfully lower Ozone-HH ($Veg2015_M$, $Veg2010_M$), land use (Veg2015 and Veg2010 for both sexes), freshwater eutrophication (Veg2015 and Veg2010 for both sexes), and marine eutrophication (Veg2015 and Veg2010 for both sexes), their GWP can be considered comparable to the CDP (only for $Veg2015_F$, $Veg2015_M$, and $Veg2010_M$). The $Veg2010_F$ dietary pattern could result in greater GWP as shows by the statistical analysis. However, the two vegetarian and the vegan dietary patterns showed a potential to improve human health by lowering the emissions-related negative impacts on human health and by offering protections against dietary risk of diseases. Health benefits offered by HealthyUS diet were negated by increased GWP and other environmental impacts that affect human health. The study demonstrated the importance of including consumer phase in LCA studies of food systems as food waste and resource use at the consumer stage was primarily responsible for increased cradle-to-grave GWP of Veg2015 and

Veg 2010. Contribution of pulses in improving food systems sustainability and human health was also highlighted in the study. Pulses provided 41 – 42% of total dietary protein in the Vegan2010 dietary pattern, while contributing only 0.79 – 0.84% of total GWP. Overall, it can be concluded that vegan dietary patterns are the best option to improve environmental sustainability of the food systems and improve human health followed by vegetarian diets. These benefits can be further amplified by decreasing food waste at the consumer and retail phases and/or by partial substitution of dairy in vegetarian patterns with dairy alternatives.

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Chapter 4 Estimation of environmental impacts of increased consumption of pulses in the United States using consequential life cycle assessment

Abstract

Environmental impact associated with increased consumption of pulses in the United States was estimated using consequential life cycle assessment (CLCA). The objective was to evaluate impacts associated with a scenario where pulse crops instead of beef are used to fulfill current or increasing demand for protein. The functional unit (FU) of the study was 9 essential amino acids (histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine), zinc, and iron equivalent to those in 100 g of beef. Amino acids in pulses were supplemented with those in rice to match the concentration of methionine with beef. This required 135 g of pulses and 100 g of rice at the processor gate. The system boundary was set to cradle-to-processor gate to include multifunctional processes. System expansion was used to handle multifunctionality of processes in CLCA. The results of CLCA were compared with attributional LCA (ALCA) that used allocation for coproducts. The study indicated that increased demand for pulses would require increasing production of both pulses and rice to match the methionine concentrations in beef. This would increase the GWP by 0.34 kg CO_2e per FU. However, GWP induced due to indirect land use change associated with expansion of arable land would further increase the GWP to 0.53 kg CO_2e per FU. Increased production of these two crops would also increase fossil resource scarcity by 42 g oil eq, land use by 1.22 m^2a crop eq (area*year), water consumption by 113 L, freshwater eutrophication 0.15 g N eq, and marine eutrophication by 0.54 g N eq. This increase in the environmental impact would still be lower than if increased demand for protein were to be fulfilled by increasing production and processing of beef, which would increase GWP by 8.22 kg CO_2e per FU (includes 3.92 kg CO_2e associated

with iLUC). A similar conclusion could be drawn for a scenario where current consumption of beef (impacts measured with ALCA) were to be substituted by increasing the production of pulse and rice (impacts measured with CLCA). While increasing the production of pulses and rice would increase the environmental impacts, the contribution of pulses was estimated to remain lower than rice for all impact categories other than LU. However, increased production of pulses would also increase coproduction of broken pulses for animal feed. This would displace soybean meal, traditionally used for animal feed as well as soybean oil, the coproduct of soybean meal production. Cascading effect of this displacement would increase the production of palm kernel oil and palm kernel meal, which if used in animal feed may require increased production of energy feed to compensate for energy differences between soybean and palm kernel meals. This was partially responsible for increased WC and ME observed for pulse and rice product chains. It must be noted that the results of this study primarily indicate directionality in the environmental impacts resulting from increased demand for pulses. Total substation of beef with pulses and rice is not recommended considering the difference in energy provided by these foods. Further nutritional study is necessary before any dietary changes are made.

4.1 Introduction

Current diet in the United States is characterized by lower than recommended consumption of nutritious fruits, vegetables, pulses, and whole grains and overconsumption of animal-sourced protein, especially, red meat (USDA and HHS, 2020). Studies have consistently shown that overconsumption of red meat is detrimental to human health. It increases the risk of diseases such as Type 2 diabetes, heart failure, coronary heart disease, and stroke (Abete et al., 2014; Al-Shaar et al., 2020; Bechthold et al., 2019; Ekmekcioglu et al., 2018; Feskens et al., 2013; Kazemi et al., 2021; Key et al., 2019; Micha et al., 2017b, 2017a; Schwingshackl et al., 2017; Vieira et al., 2017; Wolk, 2017, 2017; Yang et al., 2016; Yip et al., 2018). Moreover, agriculture in general and animal-sourced food in particular also contribute to greenhouse gas (GHG) emissions, increased water stress, environmental degradation, and biodiversity loss (Gerber et al., 2013; Searchinger et al., 2019). Compared to plant-based foods, production, processing, and distribution of foods of animal origin is also associated with greater GHG emission intensities (Clune et al., 2017), land use (Searchinger et al., 2019), and consumptive blue water use (Kim et al., 2020). Partial substitution of meat with plant-based protein has a potential to decrease land use, methane, and nitrous oxide emissions, increase carbon sequestration, and lower the cost of limiting the concentration of GHGs below 450 ppm CO_2e (Stehfest et al., 2009). This dietary change is also necessary to achieve the target of limiting increase in global temperatures to 1.5°C to 2°C and limit the severity of climate change (Clark et al., 2020).

While many plant-based protein alternatives to meat exist, pulses can be considered a superior source of protein in terms of their nutritional quality and health benefits (Röös et al., 2020). Pulses are an excellent source protein, with protein content ranging between 18 and 36% (FAO, 2016). Compared to the animal-sourced protein, pulses are rich in dietary fiber, unsaturated fatty acids, folate, and low in saturated fatty acids and cholesterol (Röös et al., 2020). They are also low on glycemic index making them an excellent source of protein to manage or prevent heart disease or type 2 diabetes (Clemente and Olias, 2017; Messina, 2014). In fact, meta-analysis of studies has shown that increased consumption of pulses can decrease the risk of coronary heart disease by as much as 33% (Afshin et al., 2014; Bechthold et al., 2019; Viguiliouk et al., 2019). Compared to other sources of dietary protein pulses have lower greenhouse gas (GHG) emissions (per unit mass of protein), thus lowering their impact on environment (Chapter 3). Moreover, when included in rotation with cereals, pulses can increase the yield of following cereal, decrease their nitrogen demand, and help break disease cycle (Burgess et al., 2012; Campbell et al., 1992; Miller et al., 2018; Walley et al., 2007; Zentner et al., 2001). Moreover, compared to other alternatives to animal-sourced protein such as plant-based meat alternatives and cultured meat, pulses can be easily included in the diet without requiring high technological innovations, thus offering high sustainability gains (van der Weele et al., 2019). This could make pulses one of the most environmentally sustainable and nutritious sources of protein in diets.

While average pulse consumption in the current US diet remains below recommended amounts (USDA and HHS, 2020), a steady increase in domestic availability of pulses to the consumer has been observed, indicating increasing consumption (USDA Economic Research Service, 2019). This upward trend in pulse consumption in the US was attributed to change in consumer preference for healthier and varied snacks and increased demand for gluten-free food products (Bond, 2017). Moreover, the global demand for protein is expected to increase with increasing population and socio-economic factors such as increasing income levels (Henchion et al., 2017). This is also expected to double the demand for animal-sourced protein, which is inherently inefficient to produce, by 2050 (Westhoek et al., 2011). Therefore, the first objective of this study was to estimate the environmental impact of increased consumption of pulses in the United States using life cycle assessment (LCA). Considering projected increased demand for animal-sourced protein, environmental impact associated with increased production of beef was also evaluated in the study. In a second objective a scenario where increased demand for protein is fulfilled by pulses instead of beef was evaluated. Decision to choose beef as a dietary source of protein that is substituted by pulses was guided by its greater environmental (Clune et al., 2017) and human health impact (Wolk, 2017) that could be potentially avoided by increased consumption of healthier pulses.

While LCA studies of pulses and beef exist (Bandekar et al., 2022; Kulshreshtha et al., 2013; MacWilliam et al., 2015, 2014; Memecek et al., 2008; Rotz et al., 2011, Tidåker et al., 2021), these studies used attributional LCA (ALCA), which is considered retrospective LCA that estimates the fraction of system environmental impact and resource utilization that is attributable to a specified functional unit (FU) (Ekvall et al., 2016). LCA studies estimating future environmental impacts associating with increased consumption of pulses and beef could not be found. We hope to fill this knowledge gap by using consequential LCA (CLCA) paradigm, which is considered prospective LCA used to estimate changes to the total system environmental impact and resource utilization caused by changes to the delivery of specified FU (Ekvall et al., 2016, Ekvall and Weidema, 2004; Rebitzer et al., 2004). One of the differences between ALCA and CLCA is handling of product and byproduct. In ALCA allocation is frequently used to handle product and byproducts, while in CLCA allocation is avoided by system expansion (European Commission. Joint Research Center. Institute for Environmental Sustainability., 2010). These methodological differences may influence the results of LCA studies. Therefore, both methodologies were used in the study to compare their influence on the results. Moreover, this allowed to compare a substation scenario increased production of pulses (CLCA) substituted current demand for beef (ALCA)

4.2. Material and Methods

4.2.1 Goal and scope

The goal of the study was to estimate the impact of increased consumption of pulses in the United States resulting from increased demand for pulses and from substitution of beef with pulses. The system boundary was set to cradle-to-processor gate, which involved farm production and upstream activities for both pulses and beef, followed by activities at the processor (Figure 4.1). Treatment of multifunctionality is what differentiates ALCA and CLCA. Such multifunctionality primarily occurs at the processing stage and is rare at the retail or consumer phases. Therefore, retail and consumer phases were excluded from the study. Environmental impact in the study was estimated in terms of global warming potential (GWP), water consumption (WC), land use (LU), fossil resource scarcity (FRS), freshwater eutrophication (FE), and marine eutrophication (ME) using ReCiPe 2016 (H) midpoint (Huijbregts et al., 2017) life cycle impact assessment (LCIA) method. In ALCA, mass-based allocation was used for system involving pulses, while economic allocation was used for beef.

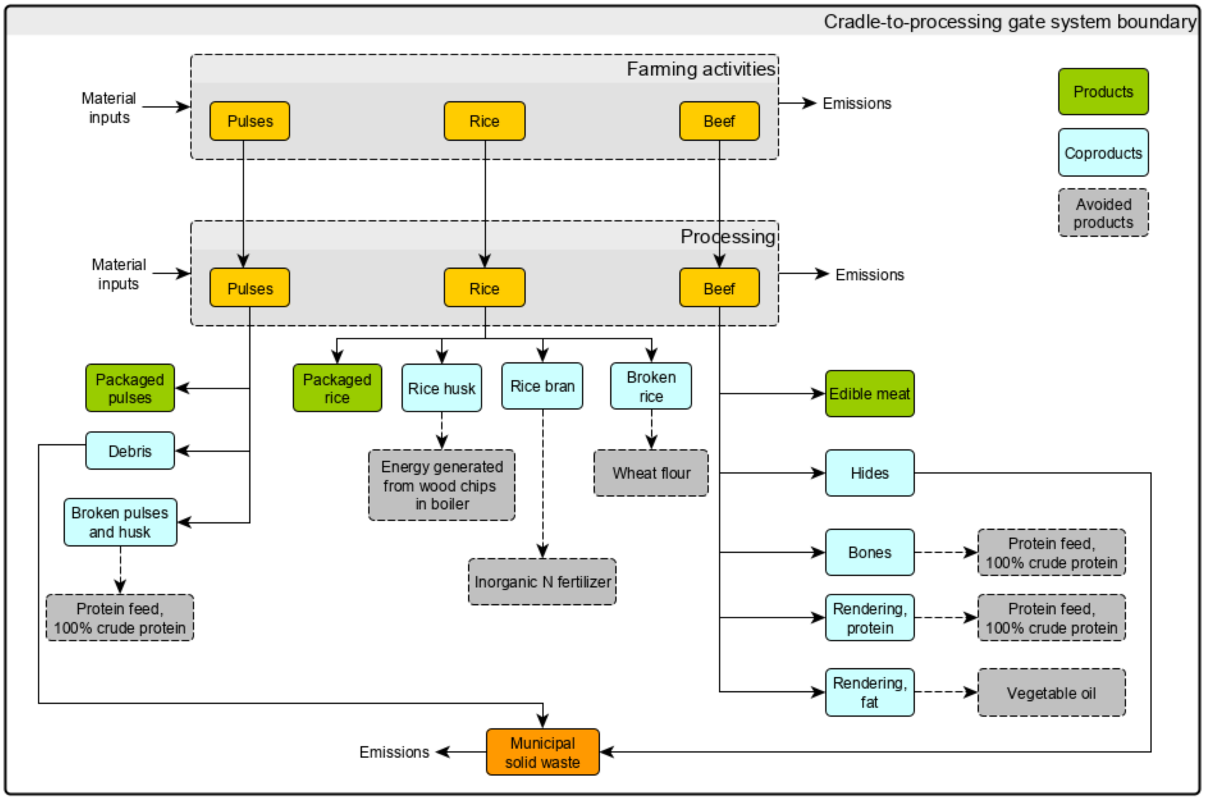

Figure 4.1- Conceptual model describing cradle-to-processing gate activities, products and coproducts generated the processing phase, and system expansion used to model marginal products displaced by coproducts.

The choice of allocation in ALCA depended on source of life cycle inventory (LCI) and availability of data.

Estimating the impact of product substitution (in this case, pulses replacing beef in human diet) using CLCA requires that the competing product (pulses) must fulfill all obligatory properties of the product (beef) (Ekvall and Weidema, 2004; Weidema, 2003). The product being substituted in this study is beef, the obligatory property of which is delivery of protein. However, protein is composed of several essential and non-essential amino acids, which are necessary for normal functioning of the body (Lopez and Mohiuddin, 2022). While non-essential amino acids are synthesized by the body, essential amino acids must be obtained only through diet (Lopez and Mohiuddin, 2022). Therefore, the FU of the study was delivery of essential amino acids equivalent to those obtained from 100 g of lean beef. Essential amino acids included histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine (National Library of Medicine, 2022). Besides these amino acids, delivery of zinc and iron was also considered in analysis. It must be acknowledged that the preference to consume beef relies primarily on personal preferences such as liking to the taste and sometimes on cultural practices. While these properties are important, they are considered ‘positioning properties’ in CLCA and influence extent to which product substitution would occur (Weidema, 2003). When defining the FU only obligatory property was considered because it decides whether product can be substituted with an alternative.

4.2.2 Life cycle inventory and LCA models

Selecting amino acids delivery as a FU was necessitated by the differences in amino acid profiles of beef and pulses. While both products provided similar concentration of protein, concentration of methionine in pulses was approximately 51% lower than beef (Table 4.1).

Considering the significance of methionine in regulating metabolism, immune system, and digestive functions (Martinez et al., 2017), matching the methionine content was necessary. Moreover, because of methionine deficit in pulses, it was considered an obligatory property in CLCA methodology, which a competing product must fulfill. Traditionally, pulses are often consumed with cereals such as rice or wheat in part of the world where pulses are the main source of dietary protein. This complementation of pulses with cereals has been proven in studies, where consumption of chickpea and rice in 3:1 ratio or lentil and rice in 1:1 ratio was reported to improve the quality of protein and availability of methionine in human diet (Rafii et al., 2020, 2022). Therefore, a combination of 135 g of pulses and 100 g of rice (pulses+rice) was used in the study to fulfill the FU. This ratio was based on an average amino acid profile of 29 species/varieties of pulses (Table C.1) and 8 varieties of rice (Table C.2) (USDA-Agricultural Research Services, 2022a).

Table 4.1- Nutrient concentrations in 100 g of pulses, rice, and beef

Nutrient	Pulses[1]	Rice[1]	Beef[2]	Pulses+rice[3]
Energy, kcal	344.56	361.75	138.00	825.96
Protein, g	22.84	7.97	22.20	38.73
Histidine, g	0.64	0.20	0.77	1.06
Isoleucine, g	1.01	0.34	1.00	1.71
Leucine, g	1.84	1.75	0.64	3.00
Lysine, g	1.52	0.31	2.03	2.35
Methionine, g	0.29	0.20	0.59	0.59
Phenylalanine, g	1.24	0.42	0.87	2.09
Threonine, g	0.90	0.28	0.99	1.49
Tryptophan, g	0.26	0.10	0.23	0.45
Valine, g	1.17	0.48	1.06	2.06
Zinc, mg	3.28	1.96	4.86	6.38
Iron, mg	6.83	2.02	2.08	11.21

[1] Average of amino acid concentration in 29 species/varieties of pulses and 8 varieties of rice (USDA-Agricultural Research Services, 2022a). [2] Obtained from Food Data Central (USDA-Agricultural Research Services, 2022a). [3] Pulses+rice includes 135 g of pulses and 100 g rice

LCA models in this study were created in OpenLCA (GreenDelta) software using EcoInvent 3.7 cut-off database in ALCA and EcoInvent 3.7 Consequential database in CLCA for background data (Warnet et al., 2016). LCA model for pulses was adapted from Bandekar et al. (2022). The model, originally built in EcoInvent 3.3 cut-off database was reconstructed in the newer version of EcoInvent database used in the study. The farming phase of the model was used without any changes to the foreground LCI. Dry bean was modeled as conventionally tilled, while chickpea, field pea, and lentil were modeled as no-till, dryland crops. However, unlike the original model that constructed processing stage for each variety of pulse crop, a market mix corresponding to the share of pulse variety in domestic market was created at the farmgate. Processing stage was modeled by Bandekar et al. (2022) to estimate and compare the environmental impact of each pulse variety. In the present study, the goal was to measure the environmental impact of increased consumption of pulses as a food group and therefore, national production mix was sufficient. Moreover, other than soaking and drying required only for chickpea and dry pea during decortication (Wood and Malcomson, 2011), the LCI at the processing stage was identical for all types of pulses. The national production mix composed of 42% dry bean, 20% chickpea, 26% field pea, and 13% lentil was created at the farmgate based on share of pulse crop species in total pulse production in the USA (Parr et al., 2019; USDA National Agricultural Statistics Services, 2020). This national production mix was used as an input to the processing stage of pulses. The LCI for processing stage was adopted from Bandekar et al. (2022).

Cradle-to-processing gate model for rice was constructed using ‘rice production, non-basmati | rice, non-basmati |’ process for the United States available in the EcoInvent 3.7 cut-off and consequential databases (Nemecek and Kägi, 2020a, 2020b) and processing stage data published by Kamalakkannan and Kulatunga (2018). The processing stage included electricity consumption for de-stoning, grading, pre-paddy cleaning, polishing, husk separation, and paddy separation. It also included 10 g of low-density polyethylene (LDPE) used for packaging (Wikström et al., 2014). Losses at the processing stage and transportation between farm and processing facility were also included in the model (Table 4.2).

Table 4.2- Life cycle inventory for 1 kg of rice packaged at the processing phase

Parameter	Rice Processing Stage
Reference flow, packaged rice, kg	1
Harvested rice hauled, kg	1.59
Electricity for de-stoning[1], kWh	0.005
Electricity for pre-paddy cleaning[1], kWh	0.003
Electricity for paddy separation[1], kWh	0.002
Electricity for grading[1], kWh	0.007
Electricity for husk separation[1], kWh	0.005
Electricity for polishing[1], kWh	0.112
Transportation to processing plant[2], t*km	0.159
Packaging film (LDPE)[3], g	10

[1] Kamalakkannan and Kulatunga (2018), Bandekar et al. (2022), Wikström et al. (2014)

LCA model for beef developed by Rotz et al. (2013) and Putman and Thoma (2019) was adapted in this study to model cradle-to-processing gate product chain of beef in the United States. This model was a comprehensive account of beef production system in the United States. Regional differences in environmental footprint of US beef were captured by Putman and Thoma (2019) by creating region-specific diet and production practices in the model. Cradle-to-processing gate part of the model, which was initially developed in EcoInvent 3.4 was reconstructed in EcoInvent 3.7 database for both ALCA and CLCA. For background data of the Soybean production process in the original model used in the production of soybean oil authors had used DATASMART database. This process was replaced in the present study with 'soybean production | soybean | Cutoff, U – US' and 'soybean production | soybean | Consequential, U – US' process from EcoInvent 3.7 database for ALCA and CLCA, respectively (Nemecek and Kägi, 2020c, 2020d).

4.2.3 Treatment of Byproducts

In multifunctional processes, emissions and resource use must be attributed to product and byproducts or coproducts. This treatment of products and byproducts is what differentiates CLCA and ALCA. Handling multifunctionality was primarily required at the processing stage for pulses and rice and at the farm (culled cattle) and processing stage for beef production. Following the guidelines about handling products and byproducts, system expansion and allocation was used for CLCA and ALCA, respectively.

4.2.3.1 Attributional LCA

Model for pulse processing developed by Bandekar et al. (2022) was modified for this study. Bandekar et al., (2022) treated broken pulses and husk as waste that is disposed to landfill. However, limited evidence suggests that these byproducts are often used in animal feed as protein and energy source (Luzardo-Ocampo et al., 2020; Nasir and Sidhu, 2012). Producing 1 kg of packaged pulses (1.52 kg of hauled and processed pulses) often generates 0.33 kg of husk and broken pulses and 0.19 kg of stones or debris. These amounts were derived by assuming that pulses hauled from the farm contain 12.5% (by mass) stones or debris and that processing cleaned and de-stoned pulses results in 25% loss in the form of husk and broken pulses (Patras et al., 2011). Considering these new findings, husk and broken pulses were treated as byproduct in this study instead of waste. A mass allocation factor was used at the processing stage to allocate resources and emission between processed and packaged pulses and byproduct of pulse processing (Table 4.3). Rice processing also involves processes and techniques similar to pulses. This results in various byproducts in the form of rice husk (20%), rice bran (8%), and broken rice (9%) (Linscombe, 2016). While these byproducts are utilized in other economic sectors in various ways, data on economic value of byproducts could not be found. Therefore, mass allocation was used for packed rice and byproducts as well (Table 4.3). Economic allocation used by Putman and Thoma (2019) was adopted into the model without any changes (Table 4.3)

Table 4.3- Allocation method and fractions used for allocating resources and burdens between products and coproducts in ALCA

Product/Coproduct		Allocation method and fractions
Pulses		**Physical – mass**
	Packaged pulses	0.75
	Broken pulses	0.25
Rice		**Physical – mass**
	Packaged rice	0.63
	Rice bran, husk, and broken rice	0.37
Beef		**Economic**
	Beef, edible, primals and cuts	0.89
	Beef, byproducts, rendering and offal	0.08
	Beef, byproducts, hides	0.03

4.2.3.2 Consequential LCA

System expansion approach used in the CLCA involved identifying products or suppliers, known as marginal products or suppliers, that would be directly affected by small short-term (marginal) changes to the demand for a product. These data were identified based on the market trend and typical usage for the coproducts. System boundaries were expanded to included product chains that the coproducts would typically substitute. Because the coproducts avoided otherwise necessary production of substituted products, expanded product chain of these products were modeled as avoided burden (Table 4.4).

Because coproducts of pulses (broken pulses and husk) are typically used in the animal feed as a source of protein, the system was expanded to include avoided burdens of protein feed. A generic market for crude protein available in EcoInvent 3.7 Consequential database was used for this expanded system. This process included supply of soybean meal, which is likely to be affected by increased availability of coproducts of pulse processing, to a generic protein feed market. The process also corrected for displacement of energy feed resulting from avoided production of soybean meal. The debris and stones separated during pre-cleaning were treated as waste to a municipal landfill.

Table 4.4- Marginal products displaced by coproducts produced during processing phase for pulses, rice, and beef

Product/Coproduct		Quantity, kg	Marginal Product	Quantity*
Pulses				
	Packaged pulses	1.00	N/A	
	Broken pulses	0.33	Protein feed, 100% crude, kg	-0.073
Rice				
	Packaged rice	1.00	N/A	
	Broken rice	0.14	Wheat flour, kg	-0.071
	Rice bran	0.13	Inorganic N fertilizers, kg	-0.003
	Rice husk	0.32	Energy generated from wood chips, MJ	-5.308
Beef				
	Beef, edible	1.00	N/A	
	Hides	0.11	Municipal solid waste, kg	0.110
	Bones	0.21	Protein feed, 100% crude protein, kg	-0.069
	Rendering, protein	0.06	Protein feed, 100% crude protein, kg	-0.001
	Rendering, fat	0.06	Vegetable oil	-0.001

* Negative sign indicates avoided production. Hides produced during beef processing at the abattoir were treated as waste, thus it carries a positive sign.

Producing 1 kg of packaged rice (finished product) would require processing 1.59 kg of paddy, which would generate generates 0.32 kg of rice husk, 0.13 kg of rice bran, and 0.14 kg of rice broken rice (Linscombe, 2016). While there are several emerging uses for these coproducts, the most established coproduct utilizations were used in the system expansion. Rice husk can be used in a boiler as fuel either through direct combustion or gasification because of its high calorific content (Hossain et al., 2018). In the United States, 42% of installed capacity (67% of installed boilers) are fueled by natural gas, followed by oil products, biomass, and coal (Schoeneberger et al., 2022). However, boiler construction varies with the physical state of the fuel (fluid vs solid) (Energy and Environmental Analysis, Inc, 2005), making biomass a marginal supplier of energy that rice husk would substitute. Therefore, heat produced using biomass was used in the study to estimate avoided burden of using rice husk as a fuel. The biomass substituted here was wood chips. Rice bran is another coproduct of rice milling that has variety of emerging novel applications in food, animal feed, nutraceutical, and pharmaceutical industries (Bodie et al., 2019). However, the scale of commercial utilization of rice bran in these industries is unknown. Moreover, Bodie et al. (2019) reported that these utilization techniques could still be in the research phase. Therefore, a traditional use of rice bran as a source of nitrogen in compost (Bodie et al., 2019) was considered in this study, which could substitute synthetic nitrogen fertilizers in agricultural. A generic market for inorganic nitrogen was modeled as avoided product. Total elemental N from synthetic fertilizers was estimated from 13% protein content of rice bran (Fabian and Ju, 2011) and elemental N to protein characterization factor (CF) of 5.95 kg N/kg protein (FAO, 2003). Because broken rice is primarily used in gluten free flours (Quiñones et al., 2015) the primary substitutable product was wheat flour. However, rice flour constitutes only 50% of the gluten-free flour, while the rest is composed of potato starch, cassava starch, millet flour, and corn flour (Quiñones et al., 2015). Therefore, only 50% of the weight of broken rice was considered to displace the wheat flour.

Beef processing system was also expanded to include avoided burdens associated with production of commodities that hides, blood and bone meal, and products of rendering would displace. In the beef model developed by Putman and Thoma (2019), boneless meat accounted for 73% of processed beef carcass, while hides and offal/rendering accounted for 8% and 4%, respectively. About 15% of carcass weight that was unaccounted for in this model was considered the weight of bones, which matched with the observed data (Jayathilakan et al., 2012; Prieto and García-López, 2014). Finding avoided or increased burden resulting from changes to the beef consumption required determining appropriate uses for these coproducts. Hides are processed by hide and leather industry into leather. In the United States, however, approximately

15% of hides end up in a landfill. If the current demand for hides remain unchanged, increased consumption of beef would increase the amount of hides sent to landfill. Therefore, hides were modeled as waste in this study. Bones along with meat meal is often used in the animal feed as a source of protein because of high concentrations of essential amino acids, minerals, and vitamin B_{12} (Jayathilakan et al., 2012). The marginal product that would likely be affected by changes to the coproduction of bone meal would be protein feed, which was considered as avoided product. Rendering of cattle parts not fit for direct consumption by humans produces various protein and fat rich products such as meat meal and tallow. The raw materials used for rendering contain 60% water, 20% protein, and 20% fat (Meeker and Hamilton, 2006). These fractions for protein and fat were used to estimate the amount of protein feed and soybean oil displaced by the final product of rendering.

Cattle farms were another stage in the beef product chain where coproducts were generated and therefore required system expansion. Cows and bulls are maintained on cow-calf farms to produce calves for beef. Throughout 2011, for example, 5898 cows and 285 bulls were maintained on these farms to produce 5050 calves (Rotz et al., 2013). These farms typically maintain a 20% replacement rate, where cattle that are past their reproductive age are replaced with calves (Putman and Thoma, 2019). The cattle are culled to produce beef substituting beef produced from the stockers, thus requiring expansion of beef system. The dressing percentage of a cull cow is only 52.7% (cold carcass weight (CCW) to live weight), much lower compared to the stockers (Blakely, 2015). Moreover, about 50% of CCW is further processed into ground meat, 15% is sold to purveyors to process into various ready to eat products, while only 5% is marketed as cuts from rib, short loin, and sirloin (Blakely, 2015). The product substituted by various cuts of meat was beef produced from stockers in the United States, while ground meat and meat sold to purveyors was considered to displace beef imported into the United States. In 2021, approximately 87% beef (carcass weight) was imported in the US was imported from Canada, Australia, Mexico, New Zealand, and Brazil (USDA-Agricultural Research Services, 2022b). Between 2017 and 2021 imports from Canada, Mexico, and Brazil have increased, while those from Australia and New Zealand have seen a decreasing trend. Increased production of beef from cull cows is likely to displace beef imports from one of these countries, most likely Canada, the largest beef supplier to the US. Beef production process for 'rest of the world' available in EcoInvent 3.7 was used for system expansion.

Culled animals on dairy farms also contribute the beef produced in the USA. In fact, approximately 10% of beef available in the US market originates from either culled bulls or culled dairy cows (Selk, 2022). Besides culled cows, other coproducts from a dairy operation include weaned calves that are sent to backgrounding operation in the beef system. The model developed by Putman and Thoma (2019) had considered exchange of animals, especially weaned calves, between dairy and beef systems. Cattle backgrounding operation in the beef system received weaned calves from dairy farms, which were sent to cattle finishing operation, and eventually to an abattoir. This approach worked well for an attributional model. In the consequential paradigm, however, system expansion was necessary, resulting in calves on dairy farms displacing weaned calves in the beef system. However, because of system expansion approach, the dairy model did not produce any weaned calves, yet supplied calves to the cattle backgrounding operation. In the initial runs, this approach provided irrational results, making the system expansion approach impractical. For this reason, the dairy system was completely omitted from the beef model. This approach was justified because culled dairy cows primarily displaced beef produced in the USA and beef imported from Canada with an underlying assumption that emission intensities of meat from beef and dairy systems are identical. Moreover, preliminary analysis indicated that GWP intensities of beef produced in the US and Canada (beef process for rest of the world process in EcoInvent 3.7) were comparable.

Eliminating dairy system from the beef model also eliminated downstream systems such as backgrounding and finishing operations for dairy calves. This consequently required increasing production from other beef systems to meet the production demand. The effect of eliminating the dairy system was modeled by equally distributing the deficit production between cow-calf-finishing and cattle finishing operations. Another consequence of eliminating backgrounding and finishing operations for dairy calves was decreased feed consumption and emissions in these operations. Therefore, credit for decreased production form these systems as applied to the beef operations. These modifications were made at a regional level in the beef model.

4.2.4 Indirect Land Use Change

Carbon emissions from land use change accounted for approximately 11% of global emission in 2020 (Friedlingstein et al., 2022). Emissions from land use change occur in two ways: 1) release of sequestered carbon on the same land resulting from crop change, termed as direct land use change (dLUC); and 2) release of sequestered carbon resulting from expansion of agricultural area or intensification, termed as indirect land use change (iLUC) (Schmidt et al., 2015). Typically, dLUC, which involves crop changes on existing agricultural land, is small and is usually excluded from the studies (Schmidt et al., 2015). However, iLUC can be a significant source of carbon emission contributing between 1.4 and 3.5 t CO_2e ha^{-1} of occupied arable land (Schmidt and Muños, 2014). This study examined the impact of shift in consumer demand towards plant-based protein obtained from pulses and rice. This increased demand for pulses and rice can be met through either expansion of agricultural area or intensification, which would result in increased GHG emissions (Kløverpris et al., 2020; Kløverpris and Mueller, 2013; Schmidt et al., 2015; Schmidt and Brandão, 2013). Considering substantial contribution of land use change to global GHG emission, iLUC was included in the study. iLUC induced GHG emissions were estimated using a world average emission factor of 1.7 t CO_2e ha^{-1} of arable land estimated by Schmidt and Muños (2014).

4.3. Results and Discussion

4.3.1 Environmental impact for FU

Environmental impacts pers FU associated with increased production and processing of pulses+rice and beef estimated using CLCA and ALCA are presented in Table 4.5.

Table 4.5- Environmental impacts associated with increased demand for pulses+rice and beef estimated using CLCA and ALCA

Environmental Impact Category	Consequential LCA		Attributional LCA	
	Pulses+rice	Beef	Pulses+rice	Beef
Global warming potential, kg CO_2e	0.34	4.31	0.32	3.47
Fossil resource scarcity, g oil eq	42.00	133.00	35.31	111.56
Land use, m^2a crop eq	1.22	22.91	1.10	15.00
Water consumption, L	133.02	265.58	68.71	185.21
Freshwater eutrophication, g P eq	0.15	0.39	0.15	0.48
Marine eutrophication, g N eq	0.54	2.19	0.34	1.68
GWP induced due to iLUC, kg CO_2e	0.20	3.92	-	-
Total GWP, kg CO_2e	0.54	8.32	-	-

4.3.1.1 Global warming potential

The GWP per FU for pulses+rice estimated using CLCA was 0.34 kg CO_2e, approximately 92% lower than beef (4.31 kg CO_2e). Within pulses+rice 92% of GWP was associated with production and processing of rice, while pulses were responsible for only 8% of the impact (Figure 4.3). Further, rice production dominated the GWP of the rice product chain (95% of GWP of pulses+rice or 0.3187 kg CO_2e per FU), with grain drying, emissions from irrigation-related fuel consumption, and production and application of synthetic N fertilizer contributing the most. Electricity consumption at the processing gate contributed less than 1% of the GWP. Similarly, production of pulses at the farmgate contributed the most to GWP in the pulses product chain, followed by drying and electricity consumption at the processing stage. Gross GWP of pulses+rice was 0.43 kg CO_2e. Avoided production of synthetic N fertilizers, wood pallets used for heat generation, and wheat flour related to rice processing and avoided

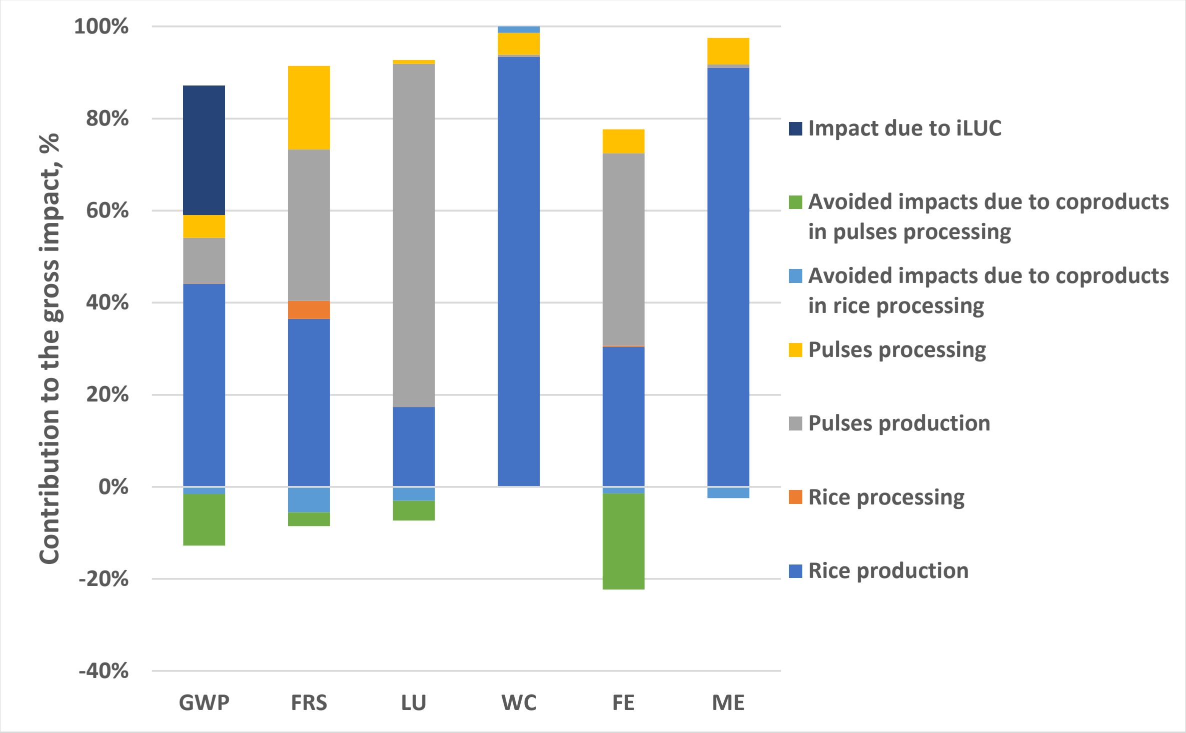

Figure 4.2- Contribution from farming, processing, and avoided production of marginal products to environmental impact categories for pulses and rice

production of protein feed related to pulse processing decreased the GWP by 0.09 kg CO_2e per FU, resulting in net GWP of 0.34 kg CO_2e. To meet the inclusion rate of pulses in the pulses+rice 180 g of pulses were necessary at the farmgate after accounting for 25% losses during processing. The GWP contribution from production of 180 g of pulses was 0.072 kg CO_2e for FU, lower than the GWP related to avoided production 0.0726 kg (0.33 kg of broken pulses multiplied by protein content 22% in pulses) of protein feed with 100% crude protein (0.081 kg CO_2e).

The largest contributor to the beef was production of cattle the farm gate (Figure 4.3), followed by natural gas consumption and other processes at the processing gate. Gross GWP for beef was 4.50 kg CO_2e per FU at the processor gate. Avoided production of vegetable oil and protein feed decreased GWP by 0.19 kg CO_2e, resulting in net GWP of 4.31 kg CO_2e. Live animal production in the southern Plains region was the largest contributor to the GWP at the farmgate (25% of total GWP), followed by production in Southeast (19%), Midwest (16%), Northeast (13%), Southwest (11%), northern Plains (9%), Northwest (8%). Top contributors to these farming activities were enteric methane emissions, emission from manure and fertilizer applications, feed, synthetic fertilizers, fossil fuels and electricity used at the farm, and pesticides; however, their contribution varied by type of cattle farm and region. Activities at the abattoir contributed only 0.104 kg CO_2e to the total climate change impact of beef.

GHG emissions due to iLUC included emissions induced due to increased demand for products analyzed in this study and changes to emissions due to decreased demand for soybean meal (Table 4.5). For the FU in the study 135 g of pulses, 100 g of rice, and 100 g of beef was required at the processor gate. Accounting for losses and coproducts during the processing this required 180 g of pulses, 159 g of rice, and 137 g of carcass weight of beef at the farm gate.

Additional arable land required to fulfill this increased demand (per FU) was 9.64×10^{-5} ha for pulses, 2.32×10^{-5} ha for rice, and 2.3×10^{-3} ha for beef at the farmgate, resulting in induced GHG emission of 0.20 kg CO_2e for pulses+rice and 3.92 kg CO_2e for beef.

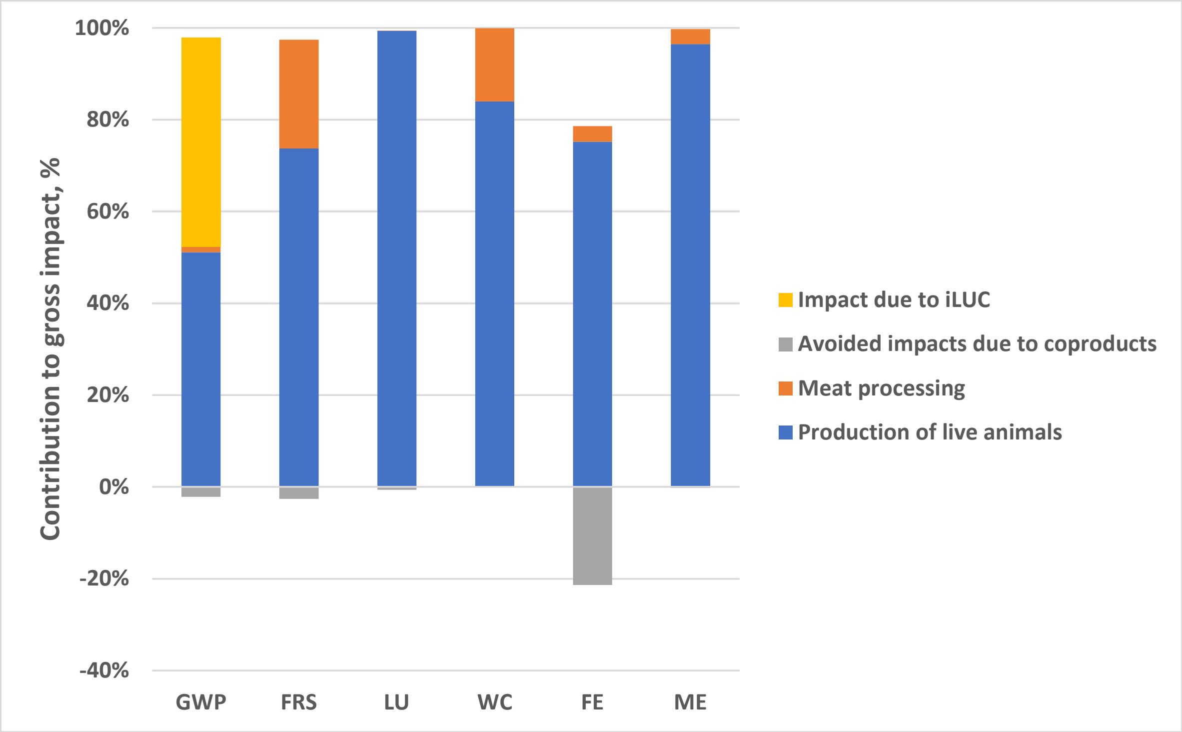

Figure 4.3- Contribution from production of live animals, processing at the abattoir, and avoided production of marginal products displaced by coproduction of beef processing

4.3.1.2 Fossil resource scarcity

FRS for pulses+rice and beef was 42 g oil eq and 133 g oil eq, respectively. Contrary to GWP contribution of pulses to FRS was greater (58%) compared with rice (42%). In both product chains, farming was the dominant contributor to FRS contributing 16 g oil eq and 18 g oil eq for pulses and rice, respectively. FRS of rice also included grain drying, which contributed 17% of total FRS. While drying was also included for pulses, it occurred at the processing stage during decortication. Drying of pulses also contributed 17% of total FRS. Production of LDPE packaging film was the third largest contributor to both pulses and rice contributing 1.5 g oil eq from pulses and 1.8 g oil eq from the rice product chain. Tillage and production of fertilizers, pesticides, and seeds were the major contributors to cradle-to-farmgate phase of pulses and rice. Gross FRS for pulses+rice was 45 g oil eq. Avoided production of protein feed decreased fossil fuel consumption in pulse product chain, thereby reducing FRS by 1.5 g oil eq (3.68% of total FRS). A greater decrease of 2.7 g oil eq (6.64% of total FRS) was observed for rice product chain.

Production of live animals (cradle-to-farmgate activities) contributed 78% of cradle-to-processor gate FRS for beef, while processing stage contributed 22%. Major contributors to FRS at the processing stage were natural gas consumption in boiler (12.39%), transportation of live animals from farms to abattoir (7.70%), and upstream activities associated with production of sodium hypochlorite (1.34%). Electricity consumption, packaging material, diesel, and other chemicals used at the abattoir were other contributors at the processing stage, however, their individual contribution was less than 1%. Gross FRS for beef was 137 g oil eq, while avoided products decreased the FRS by 3.6 g oil eq. Similar to GWP, contributors to FRS at the farmgate were feed, fossil fuels, electricity, and upstream activities associated with production of inorganic fertilizers and pesticides.

4.3.1.3 Land Use

Farm operations that included growing pulses and rice in pulses+rice system and growing feed for animals and production of live animals in the beef system were the primary contributors to LU. Contribution of activities taking place at the processing stage was less than 1% for both systems. Within pulses+rice land use was greater for pulses (83.2%) compared rice (16.8%) primarily for two reasons: 1) Pulses have lower yield compared to rice. Yield of pulses ranged from 1.34 t ha^{-1} for lentil to 2.03 t ha^{-1} for field pea, with production weighted average yield of 1.86 t ha^{-1}. Contrarily, yield of rice used in the EcoInvent model was 6.27 t ha^{-1}, at least 3 times higher than pulses. 2) The FU used 1.35 times more pulses than rice requiring more production of pulses. Lower yield of pulses and greater production demand required larger agricultural land occupation, which increased contribution of pulses to overall LU. Avoided production of protein feed resulting from increased demand for pulses decreased the LU by 0.06 m^2a, while avoided production of wheat and wood pallets resulting from rice processing decreased LU by 0.04 m^2a. Gross LU for beef was 23.1 m^2a, which decreased to 22.96 m^2a due to avoided production of protein feed (-0.14 m^2a) and vegetable oil (0.002 m^2a. At the farmgate production feed, especially corn, corn gluten meal, and alfalfa, were the major contributors to LU.

4.3.1.4 Water Consumption

WC for pulses+rice was 113 L, about 50% lower than beef (266 L). Approximately 95% of WC in pulses+rice originated from rice production, primarily because of consumptive water use associated with rice irrigation. Seed production was the second largest contributor in the rice farming, however, it only contributed approximately 3% of total WC. Gross WC of rice production and processing was 108.5 L, which was decreased to 107 L primarily because of avoided production of wheat (-1.5 L). Decrease in WC associated with avoided production of wood pallets and inorganic N fertilizer was negligible. Production and processing of pulses resulted in WC of only 6 L, primarily because pulses were modeled as dryland crops. However, WC associated with production of pulses on the farm was only 0.5 L. Low contribution of pulses was primarily because pulse crops were modeled as dryland crops. Therefore, any consumptive water use only includes embedded water consumption in upstream activities resulting from farming. Approximately 5.3 L was associated with avoided production of protein feed. The increase in WC was a result of cascading effect of avoided production of protein feed. Substituting the source of protein in animal feed with broken pulses decreased the demand for soybean meal, consequently, decreasing WC by 0.18 L. However, decreased production of soybean meal also decreased soybean oil production, to compensate for which palm oil production would have to be increased. Coproduct of palm oil production is palm kernel meal which is also often used in animal feed as a source of protein. However, because of the lower energy content of palm kernel meal compared to soybean meal production of energy feed (barley, in EcoInvent database) has to increase. This was referred to as "soybean loop" by Dalgaard et al. (2007). This increased the demand for barley increased the WC by 5.4 L. Similar cascading effect was also observed in the beef system. WC associated with avoided production of protein feed was approximately 4% (11.8 L) of total WC of beef. Cradle-to-farmgate processes were responsible for 95% of WC, while all other resources use at the processing stage accounted for remaining 1%.

4.3.1.5 Eutrophication Potential

FE and ME of pulses+rice was 61% and 75% lower, respectively, compared to beef. Production and processing of rice contributed 51% of FE and 93% of ME. However, contribution of cradle-to-farmgate phase of pulses was greater than rice (0.11 g P eq for pulses vs 0.08 g P eq for rice). At the processing stage of pulses avoided production of protein feed decreased FE by 0.06 g P eq, which would otherwise be present in absence of increased demand for pulses. This consequently lowered cradle-to-processor gate FE of pulses. P fertilizer application rate for rice was 30 kg P ha^{-1}, with the range used for pulses (28 – 34 kg P ha^{-1}). However, lower yield of pulses decreased their resource use efficiency, resulting in greater field emission intensity compared to rice. FE for beef originated almost entirely from the cradle-to-farmgate operations, which contributed 0.51 g P eq. Avoided production of protein feed as blood and bone meal and products of rendering substituted protein in animal feed decreased the FE by 0.12 g P eq, resulting in net FE of 0.39 g P eq. Transportation of live animals, packaging and sodium hypochlorite production were few of the other contributors at the processing stage but their contribution was relatively low (0.02 g P eq). This was nullified by decrease in FE associated with avoided production of vegetable oil (0.02 g P eq). At cradle-to-farm stage loss of phosphorus through leaching, sediments, and runoff associated with manure handling and fertilizer application was the primary cause of eutrophication potential.

Greater contribution of rice to total ME was primarily because of N fertilizer application rate of 139 kg N ha^{-1}. Comparatively, pulses used only 5.6 kg N ha^{-1} for chickpea, field pea, and lentil and 44.8 kg N ha^{-1} for dry bean. Farming stage of rice contributed 0.51 g N eq to ME, which was decreased to 0.5 g N eq due to avoided production of wheat, inorganic N fertilizer, and wood pallets. ME for cradle-to-farmgate phase of pulses was only 8.6×10^{-3} g N eq or 0.66% of total ME for pulses+rice. The cascading effect of avoided production of protein feed increased the contribution of production and processing of pulses to 7% for ME. Avoided production of soybean meal in the protein feed at the processing phase decreased ME by 3.78×10^{-2} g N eq, while subsequent increased demand for barley increased it by 6.95×10^{-2} g N eq. Similar impact associated avoided production of protein feed was also observed for beef, which contributed 3.2% (0.07 g N eq) of total ME (2.19 g N eq). Cradle-to-farmgate activities in beef product chain were responsible for 96.95% (2.12 g N eq) of ME, while rest of the activities contributed less than 1%. Similar to FE, emissions associated with manure handling and fertilizer application were primarily responsible for cradle-to-farmgate contribution to ME.

4.3.2 Comparison with attributional model

Environmental impact estimate by ALCA for pulses+rice was similar to CLCA for GWP and FE but lower than CLCA for other impact categories (Table 4.4). For beef ALCA estimated lower environmental impact for all impact categories, except FE. One of the reasons for these discrepancies, especially for pulses+rice, was the differences in how coproducts were handled in both methodologies. Estimated WC for pulses+rice, for example, was 61% higher with CLCA (113 L per FU) compared to ALCA (69 L per FU). In addition, contribution for the pulses product chain in CLCA was 5.3% compared to 0.8% in ALCA. In CLCA avoided production of protein feed required increased production of barley as explained in Section 3.4, which subsequently increased the WC and contribution from the pulses product chain. This cascading effect was absent in ALCA, where mass allocation was used. Similarly, because of mass allocation used in rice product chain in ALCA, irrigation WC for packaged rice was only 0.09 L per FU compared to 0.15 L per FU observed in CLCA. For same reason ME estimated by CLCA was greater than ALCA. For FRS and LU, where such cascading effect was not responsible, the combined effect of allocation and differences in coproduct handling in background processes increased impact estimated by CLCA. For beef product chain distribution of meat produced from backgrounding of dairy calves between other dairy operations may have been partially responsible for increased environmental impact estimated by CLCA, besides the effect of methodological differences.

4.3.3 Environmental impact of 1 kg of pulses

Environmental impact associated with a kg increase in production and processing of pulses (Table 4.6) are presented to differentiate it from impacts of rice. Increased demand for pulses (1 kg at processing gate) required harvesting 1.33 kg pulses at the farmgate, would increase GWP by 1.48 kg CO_2e. However, GWP associated with iLUC was responsible for 1.37 kg CO_2e. Contribution from the farming stage was 0.56 kg CO_2e, with largest contribution originating from dry bean production (0.35 kg CO_2e), followed by field pea (0.08 kg CO_2e), chickpea (0.07 kg CO_2e), and lentil (0.06 kg CO_2e). At the processing stage largest contributor was emissions associated with drying required prior to decortication (0.11 kg CO_2e), followed by packaging (0.02 kg CO_2e), and transportation (0.01 kg CO_2e). Electricity consumption for processing contributed only 0.0015 kg CO_2e to GWP. Avoided production of protein feed at the processing stage decreased the GWP by 0.60 kg CO_2e, resulting in net GWP of 0.11 kg CO_2e.

Table 4.6- Environmental impacts associated with 1 kg increased production and processing of pulses in the United States

Impact factor	Pulses
Global Warming Potential, kg CO_2e	0.11
Fossil resource scarcity, kg oil eq	0.16
Land use, m^2a crop eq	7.35
Water consumption, L	44.4
Freshwater eutrophication, g P eq	0.49
Marine eutrophication, g N eq	0.27
GWP induced due to iLUC, kg CO_2e	1.37
Total GWP, kg CO_2e	1.48

Contribution of farming stage to FRS was 82%. Similar to GWP, drying of pulses, packaging film, and transportation were major contributors to FRS, with avoided production of protein feed decreasing FRS by 6.9%. Land use associated with production of pulses (farming stage) was 7.9 m^2a crop eq, which decreased to 7.46 m^2a crop eq because of avoided production of protein feed (-0.47 m^2a crop eq). Similarly, the production phase of pulses contributed 0.86 g P eq to the FE, followed by drying, and other activities. Protein feed production avoided during processing contributed -0.41 g P eq. For WC and ME, the largest contributor to was production of energy crop (barley in this case), resulting from avoided production of protein feed as explained in Section 3.1.4. This cascading effect increased WC by 39 L and ME by 0.23 g N eq. Contribution of farming phase to these impact categories was 4 L for WC and 0.003 g N eq for ME.

4.3.4 Implications of the study

Increased consumption of pulses as a source of protein in human diet would require complementing pulses with rice to match essential the amino acid profile supplied by beef. A single consumption of pulses+rice would increase GWP by 0.34 kg CO_2e for FU that includes 135 g of pulses and 100 g of rice. Moreover, increased demand for pulses and rice would result in induced GHG emissions of 0.20 kg CO_2e associated with iLUC, resulting in total GWP increase of 0.54 kg CO_2e. This increased demand for pulses and rice would also increase FRS by 41 kg oil eq, WC by 113 L, FE by 0.15 kg P eq and ME by 0.54 kg N eq. Moreover, 1.20 m^2a of additional land would be required to meet this demand. However, net environmental benefits in terms of the environmental impact categories examined in this study can be achieved if added demand for protein were to be fulfilled using pulses and rice instead of beef. If demand for protein (consequently essential amino acids) were to be fulfilled by increasing beef production, it would increase environmental burden in terms of GWP (8.22 kg CO_2e per FU; production related and induced due to iLUC), FRS (133 g oil eq per FU), LU (22.91 m^2a crop eq), WC (266 L per FU), FE (0.39 g P eq per FU), and ME (2.19 g N eq per FU). These environmental burdens can be avoided if new demand for protein is fulfilled through increasing production of pulses and rice instead of beef. Considering environmental impacts of current beef production and processing (measured using ALCA) are greater than environmental impacts of increased production and processing of pulses, similar environmental benefits can be attained if current demand for protein were to be satisfied by pulses and rice instead of beef.

4.3.5 Limitations

In this study, two sources of protein were compared in terms of their ability to provide essential amino acids. Because the goal of the study was to estimate environmental impact of fulfilling increased (or current) demand for protein with pulses, their amino acid profile was complemented by inclusion of rice and matched with beef, one of the largest contributors to GWP. Current inclusion rates of pulses and rice provided methionine in same quantity and other amino acids, zinc, and iron in larger quantities than beef. However, the combination of pulses and rice also increased the calorific content of the meal, providing 706 kcal compared to 138 kcal provided by beef. Therefore, substituting beef with pulses and rice in the diet may require other dietary changes to balance daily calorific intake. Estimating these dietary changes was out of scope for this study, however, they may be necessary in practice for vulnerable groups such as those suffering from obesity, diabetes, and other chronic diseases. Similarly, dietary requirement of amino acids was not considered in the study. It must be noted that methionine content in beef can be matched by consuming 156 to 311 g of pulses (dry basis) depending on pulse species and variety and completely avoiding rice. This would, however, still provide 637 to 1023 kcal at least four times higher than beef. Therefore, efforts to increase methionine content of pulses is necessary. This can be achieved through sulfur fertilization and development of transgenic varieties (Pandurangan et al., 2015).

We would like to acknowledge here that the comparison between pulses and beef as a source of protein focused primarily on environmental impacts. As noted by Pikosky et al. (2022) a more nuanced approach that integrates environmental, health, economic, and societal metrics is necessary to suggest any dietary shifts. This is especially essential for vulnerable populations that require higher quality protein and limited caloric intake. Protein quality and bioavailability of amino acids varies by the source of protein. Protein quality of animal sourced protein is usually higher, with greater than 90% digestibility (Pikosky et al., 2022) compared to 70 to 90% digestibility of protein in pulses (Nosworthy et al., 2017). The study did not consider other macronutrients as well as personal preferences that influence the choice of dietary protein as well. Studies have shown that swapping animal-sourced protein with plant-based protein or increasing the consumption of plant-based protein can lead to nutritional deficiency in terms of protein, vitamins A and D, and calcium in children and elderly populations (Cifelli et al., 2016; Houchins et al., 2017). Moreover, switching to plant-based protein such as pulses may require changing consumer behavior, learning new cooking skills (Pikosky et al., 2022) as well as acquiring liking for the new taste. These factors may affect acceptance of pulses as a source of protein and negatively influences protein and nutritional intake.

Another limitation of the study stemmed from the variability around induced GWP CF associated with iLUC. The uncertainty associated with this CF is well documented. For example, Schmidt et al (2015) reported that induced GWP from iLUC for 1 MJ biofuel could vary between -150 g CO_2e to 150 g CO_2e depending on biofuel feedstock and marginal suppliers used in the study. A recent review of iLUC methodologies found that despite recent improvements, large uncertainty, and low confidence in iLUC factor still persist (Daioglou et al., 2020). In this study a global average GWP impact factor was used to capture the effect of iLUC. A characterization factor derived from biophysical, economic, or rule-based model may yield different results for GWP associated with iLUC (Schmidt et al., 2015). However, this was out of scope for the study. While substituting beef in diet with pulses may aid in decreasing environmental impact, the true magnitude of decrease in GWP associated with iLUC may not be estimated accurately. Besides variability in the iLUC GWP CF, predicting future use of land freed by decreased consumption of beef is difficult. Reforestation on this land may increase carbon sequestration, thereby decreasing GWP, while urban development could haven an opposite effect while also disrupting hydrology of the area. Moreover, impact of iLUC on ecosystem services and on species loss was not considered in this study as well. Deforestation in part of the world that hosts endangered species may further threaten environmental balance necessary for healthy planet.

Besides this variability and uncertainty around iLUC factor, an assumption that increased demand for pulses was fulfilled by expansion of arable land was another source of uncertainty in the study. Long et al. (2014a, 2014b) reported that farmers in Northern Great Plains are adopting cereal-pulses cropping system instead of inefficient cereal-fallow sequence. While pulses are primarily replacing fallow in the rotation for socio-economic reasons (Long et al., 2014a), pulses displace environmentally harmful pesticide application in the fallow system that does not provide any revenue to the farmer or contribute to food availability. If the trend reported by Long et al, (2014a, 2014b) continues in the future, increased demand for pulses could be fulfilled by bringing more fallow land under pulse production. In this case the GWP induced by iLUC could be lower than estimated in this study, because iLUC would be influenced only by additional land required for rice production. By current estimates GWP induced by pulses+rice was 0.2 kg CO_2e per FU, with increased production of pulses contributing 0.16 kg CO_2e from iLUC. If replacement of fallow by pulses is considered dLUC, then GWP induced by iLUC for pulses+rice would be only 0.04 kg CO_2e per FU. However, applicability of this approach in CLCA must be studied further.

4.4. Conclusion

The study showed that including pulses in diet as a source of protein and complementing their amino acid profile with rice would result in lower environmental impact compared to beef.

Net environmental impact associated with pulses+rice per FU would be 0.34 kg CO_2e for GWP, 41 g oil eq for FRS, 1.24 m^2a crop eq for LU, 113 L for WC, 0.15 g P eq for FE, and 0.54 g N eq for ME. The environmental impact would be 57% to 95% lower for various impact categories than beef. Within pulses+rice, irrigated rice was responsible for majority of environmental impact for all impact categories other than LU. Lower yield of pulses increased their demand for LU, effectively also increasing iLUC induced GWP, which was 1.37 kg CO_2e per kg of pulses at the processor gate compared to 0.43 kg CO_2e per kg of rice. Broken pulses produced during processing of pulses helped decrease environmental impact of pulses for most impact categories. However, this avoided production of soybean meal used as protein feed required increasing the production of barley, which increased WC and ME for pulses+rice.

Overall, net environmental gains can be achieved if increased demand for protein in the future can be fulfilled through pulses instead of beef. A steady substitution of beef with pulses in current human diet can also help accomplish same results. Further study using economic partial or general equilibrium model may be necessary to accurately estimate induced GWP impact associated with iLUC. The impact of iLUC on ecosystem services and species loss may be necessary as well. While pulses could be a sustainable source of protein, their sustainability could be improved by increasing their yield potential. Increased yield potential may be particularly necessary to minimize or avoid impacts associated with iLUC. A study comparing environmental impact of increased production of pulses with sources of protein other than beef could also help understand and improve their sustainability.

Most importantly, the results of this study must be considered only as directional change that may occur by partial substitution of pules in diet. Because pulses supplemented with rice provide higher calories compared to beef, any substitution may require careful dietary adjustments. Complete substitution of animal-sourced protein with pulses is not recommended without balancing other macro and micro nutrients. Other factors such as personal preferences for taste, cooking skills etc. must also be considered, especially because these influence dietary intake and cause nutritional deficiency.

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Nemecek, T., Kägi, T., 2020c. soybean production | soybean | Cutoff, U – US, ecoinvent database version 3.7.

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Chapter 5 Conclusion

5.1 Research summary

The goal of this dissertation was to estimate environmental and human health impacts of pulses produced and consumed in the United States. Sustainability and health impacts of pulses were measured in terms of 1) impact on the environment associated with current production and consumption practices, 2) contribution of pulses to detrimental health impacts associated with emissions from food system and beneficial health impacts associated with healthier dietary choices made by the consumer, and 3) changes to current global environmental impacts caused by increased demand for pulses. Research on these topics for pulses grown in the United States is either absent or limited. In this dissertation, we attempted to fill these gaps in the scientific knowledge with a hope that consumers, growers, and policy makers can make informed decisions with the help of results of this and other similar studies.

Environmental impact assessment of current production and consumption practices of pulses conducted in Chapter 2 identified consumer phase as a hotspot in the pulse product chain. The consumer phase contributed at least 83, 81, 76, 75, and 87% of total impact for global warming potential (GWP), fossil resource scarcity (FRS), water consumption (WC), freshwater eutrophication (FE), and marine eutrophication (ME), respectively in baseline open vessel cooking (OVC) scenario. As expected, the farming stage was the largest contributor to land use (LU). The primary reason for greater impact from the consumer phase was time and consequently, electricity consumption required for cooking pulses. Switching to pressure cooking decreased the contribution from consumer phase as well as overall impact of pulses, especially for GWP, FRS, FE, and ME. Greater and statistically significant decrease in these impact categories was observed for electric pressure cooker (EPC) compared to OVC and stovetop pressure cooker (SPC). Shorter cooking time due to cooking under increased pressure and lower energy losses due to insulated heating element were the primary reasons EPC had the lowest environmental impact. Any observed differences in mean LU and WC scores in relation to cooking method were found to be statistically non-significant. Besides cooking method, the amount of pulses cooked in a batch also affected the environmental impact of pulses. Cooking 1.25 kg instead of 66 g of pulses decreased GWP by 86, 84, 82, and 68% for chickpea, dry bean, field pea, and lentil, respectively, even when open vessel cooking was used for both quantities. This was primarily because cooking in large quantities improved the resource use efficiency as cooking time was only marginally affected by batch size.

Cradle-to-farmgate environmental impact of pulses was also measure in the study, which was 0.32 to 0.61 kg CO_2e was GWP, 0.08 to 0.16 kg oil eq for FRS, 5.40 to 7.80 m^2a crop eq for LU, 3.09 to 4.99 L for WC, 0.59 to 0.84 g P eq for EP and 0.018 to 0.027 g N eq for ME. The impact for cradle-to-farmgate phase was influenced by yield of pulses, land management practices, and demand for fertilizers. Overall, the environmental impact was lowest for field peas, which had the greatest yield, and greatest for dry bean, which had larger N fertilizer demand and were modeled to use conventional tillage. Chickpea and lentil had lower yields and similar resource use as field pea resulting in greater environmental impacts compared to field pea.

In Chapter 3 environmental and human health impacts of current and recommended dietary patterns that contained varying amounts of pulses were compared using hybrid-LCA and Combined Nutritional and Environmental LCA (CONE-LCA) frameworks. The GWP of diets ranged between 7.89 and 11.69 kg CO_2e/capita/day for females (1800 kcal) and between 10.21 and 15 kg CO_2e/capita/day for males (2400 kcal). Compared to current dietary pattern (CDP), healthy-style US diet (HealthyUS) showed greater environmental impact, which was found to be statistically significant in the uncertainty analysis. Similarly, lower environmental impact compared to CDP observed for vegan dietary pattern (Vegan 2010) was statistically significant for both sexes. Two vegetarian recommended dietary patterns (RDP), Veg2015 and Veg2010, compared in this study were found to lower (statistically significant) ozone formation, human health (Ozone-HH); LU; FE; and ME but their GWP can be considered similar to CDP. The difference in mean impact scores between CDP and these two vegetarian patterns were found to be statistically non-significant during the uncertainty analysis. While all RDPs offered net benefits to human health, emission-related adverse effects on human health associated with HealthyUS negated any consumption-related benefits. Overall, greatest net benefits to human health were offered by Vegan2010, followed by Veg2010, and Veg2015. Pulses provided 41 – 42% of total dietary protein in the Vegan2010 dietary pattern, while contributing only 0.79 – 0.84% of total GWP. Moreover, compared to other sources of protein, pulses showed better nutritional density as indicated by their NRF9.3 scores and lower GWP. Out of gross health benefits offered by RDPs approximately 2 to 8% could be attributed to pulses, with largest contributions to Vegan2010 dietary pattern.

Environmental impacts associated with increased demand for pulses were estimated in Chapter 4 using consequential LCA. To provide essential amino acids similar to those found in 100 g of beef, 135 g of pulses were complemented100 of rice. It was observed that increased demand for pulses in the United States would increase the environmental impact associated with pulse and rice production and processing. However, this increased environmental impact would still be 94, 68, 95, 57, 61, and 76% lower for GWP, FRS, LU, WC, FE, and ME, respectively than environmental impact associated with increased demand for beef. Within pulse and rice product chains contribution of pulses was lower for GWP, FRS, WC, FE, and ME primarily due to lower nitrogen and phosphorus requirements of pulses compared to rice. Moreover, pulses were modeled as dryland crops while rice required irrigation, which increased GWP, FRS, and WC of rice. The LU contribution of pulses was greater in the pulse and rice product chain because of lower yield of pulses. Increased demand for pulses was also estimated to increase coproduction of broken pulses at the processing phase. Substitution of protein feed in animal diet by these broken pulses would increase the demand for barley (marginal product of soybean meal), thereby increasing the WC and ME of pulses and rice system. However, compared environmental impacts from increased (results of CLCA) or current (results of ALCA) demand for beef, increased demand for pulses and rice would be lower.

Based on the information learned in these three chapter it can be concluded that:

1) Compared to other sources of protein, both of plant and animal origin, pulses have better nutritional quality and lower environmental impact, potentially making them one of the most sustainable and nutritionally dense sources of protein.
2) Substitution of animal-sourced protein in diet with pulses can contribute to decreasing diet related disability adjusted life year (DALYs) and thus to improving human health. However, this may also require other dietary adjustments to ensure all nutritional requirements are met. Following dietary recommendations made by authorized agencies such as United States Department of Agriculture and United States Department of Health and Human Services would be an appropriate option.
3) Increased demand for pulses would require increasing their production and processing, which may result in increased environmental impact. However, net environmental gains

can be attained if pulses replace protein sources such as beef, which have higher environmental impact than pulses.

4) However, sustainable consumption of pulses would require changes to consumer behavior in terms of adoption of cooking methods that reduce cooking time and conserve energy. This may include cooking pulses in electric pressure cooker or in larger batches. However, care must be taken to avoid food losses if later option is chosen as food losses can contribute to increased environmental impact of food sources.
5) Considering that the environmental impacts, especially of the farming stage, are influenced by yield, efforts are necessary to increase the yield potential of pulses to improve their sustainability metric.
6) Improved yield potential may also decrease their environmental impact associated with increased production. This could happen through increased resource use efficiency at the farming stage and thorough elimination or reduction in expansion of arable land required to meet increased demand. The first pathway would decrease production related environmental impacts, while the later would help in decreasing induced GWP due to indirect land use change (iLUC). Moreover, GWP due to iLUC could be potentially decreased if increased demand for pulses could be fulfilled by growing dryland pulses on land under summer fallow.
7) One of the shortcomings of pulses is their low methionine concentration compared to animal-sourced protein such as beef. The methionine concentration could be increased through either sulfur fertilization or breeding. These efforts could decrease the amount of pulses necessary to match methionine concentrations in other sources of protein, thereby decreasing environmental impacts as well as caloric-consumption in human diet.

5.2 Future direction

This research work successfully evaluated sustainability and health impacts of pulses. However, limitations identified in each study would provide an excellent opportunity for future research on pulses.

1) In Chapter 2, national average production practices were used to create life cycle inventory (LCI) for farming activities. These data were derived from discussions with experts and based on reports by extension agencies. Efforts were made to capture variability through uncertainty analysis. However, actual production practices may differ from region to region, which could be captured through either crop model simulations or surveys. Data obtained from such methods would allow to capture variability in production practices and consequently in the LCI. Crop simulation may also provide more accurate estimates of field emissions related to fertilizer use in the production of pulses.
2) In Chapter 3, environmentally extended input-output model was used to obtain LCI for cradle-to-processor gate activities in the food system. This model, composed for year 2002, was adjusted using produced price index (PPI) to represent 2018-dollar value. However, an intrinsic assumption in this method was that underlying structure of the US economy and therefore, share of share of each sector to the environmental impacts remained unchanged. Similarly, data for retail sector and retail prices were for 2011 and 2010, respectively. Therefore, more recent data could be used in the future research work. It must be noted, however, that this may change the quantitative result of the study. We expect the directional results observed in present study would remain unchanged.

Nonetheless, use of more recent data in future study may provide a validation if the results and conclusions could be repeated.

3) In Chapter 4, iLUC induced GWP was estimated using global average characterization factor. It is difficult to predict today how land use change would be influenced by increased demand for pulses as it depends on price and yield elasticities and technological changes in the future. However, economic partial or general equilibrium models may offer better understanding than using global average characterization factor. Therefore, future research may focus on implementing these models to obtain better estimates of characterization factor iLUC induced GWP. Future study can also take more nuanced approach by considering societal and economic metrics that often influence dietary choices.

Appendix A – Supplementary material for Chapter 2

Table A.1- Production, export, and domestic availability of various pulse species in the United States

Pulse Variety	Production[1]	Export[2]	Domestic Availability	Percentage of domestic availability[3]	Per capita availability[4]	Household spending on pulses[5]	Allocation used[6]
	1000 CWT	1000 CWT	1000 CWT		lbs./year	$/household	%
Dry beans	26,773	6,260	26,766,740	-	6.40	21.73	0.36
Chickpea	12,742	2,463	12,739,537	34	1.23	4.19	0.07
Lentils	8,408	3,535	8,404,465	22	0.81	2.76	0.05
Field peas	16,442	5,152	16,436,848	44	1.59	5.41	0.09

[1] USDA National Agricultural Statistics Service (2017)

[2] Parr et al., 2019

[3] Calculated as percentage of total chickpea, lentil, and field pea domestic availability

[4] Estimated using 2017 USDA Loss Adjusted Food Availability database (USDA Economic Research Service, 2019) for dry peans and lentils and domestic availability of chickpea, lentil, and peas (Percentage of domestic availability column)

[5] Estimated using consumer price index of 1.342 $/lbs. (U.S. Bureau of Labor Statistics, 2018) and average household size of 2.53 (U.S. Census Bureau, 2019)

[6] Estimated using total household food expenditure of $6114.18 and household spending on

Table A.2- Cooking instructions for various type of pulses obtained from USA Dry Pea & Lentil Council, (2019)

Pulses variety	Water for soaking	Pulses	Water for cooking	Simmer after boil
	Cups (g)	Cups (g)	Cups (g)	Min
Chickpea	3 (710)	1 (203)	3 (710)	90
Dry bean	3 (710)	1 (195)	2 (473)	90
Field pea	-	1 (209)	2 (473)	38
Lentil	-	1 (209)	2.5 (592)	19

Table A.3- Cooking instruction for various types of pulses for cooking in stovetop pressure cooker (SPC)

Pulses variety	Water for soaking	Pulses	Water for cooking	Average Cooking time[1]
	Cups (g)	Cups (g)	Cups (g)	Min
Chickpea	3 (710)	1 (203)	3 (710)	13
Dry bean[2]	3 (710)	1 (195)	3 (710)	7
Field pea[3]	-	1 (209)	3 (710)	15
Lentil[4]	-	1 (209)	3 (710)	7

[1] Source- FastCooking (2019) and Hawkins Ventura (2003). Chickpea and dry bean were soaked prior to the cooking, while field pea and lentil were cooked unsoaked.

[2] Average of cooking times for Adzuki beans, Anasazi beans, black beans, cranberry beans, flageolet beans, great northern beans, kidney beans, pinto beans, red beans, scarlet runner beans, small navy beans, white kidney beans

[3] Average of cooking times for black-eyed peas; pigeon peas; peas, split, green or yellow; peas, dried, whole

[4] Average of cooking times for lentils; lentils, French green; lentils, green, mini (brown); lentils, red, split; lentils, yellow, split (moong dal)

Table A.4- Cooking instruction for various types of pulses for cooking in electric pressure cooker (EPC)

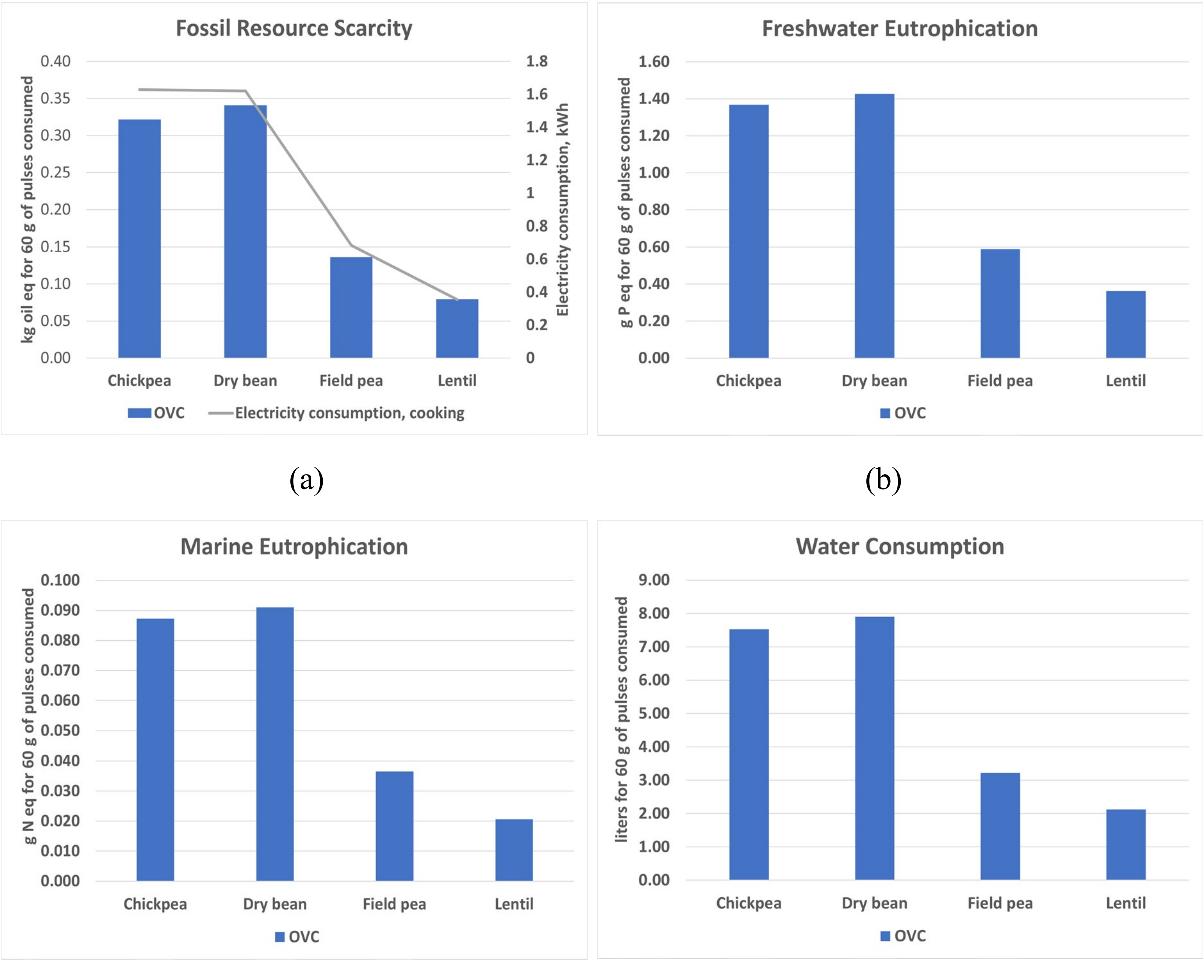
Pulses variety	Water for soaking	Pulses	Water for cooking	Average Cooking time[1]
	Cups (g)	Cups (g)	Cups (g)	Min
Chickpea	3 (710)	1 (203)	3 (710)	13
Dry bean[2]	3 (710)	1 (195)	3 (710)	7
Field pea[3]	-	1 (209)	3 (710)	21
Lentil[4]	-	1 (209)	3 (710)	5

[1] Source- Instant Brands Inc (2020). Chickpea and dry bean were soaked prior to the cooking, while field pea and lentil were cooked unsoaked.

[2] Average of cooking times for Adzuki beans, Anasazi beans, black beans, red kidney beans, white kidney beans, navy beans, pinto beans

[3] Average of cooking times for black-eyed peas, peas, pigeon peas

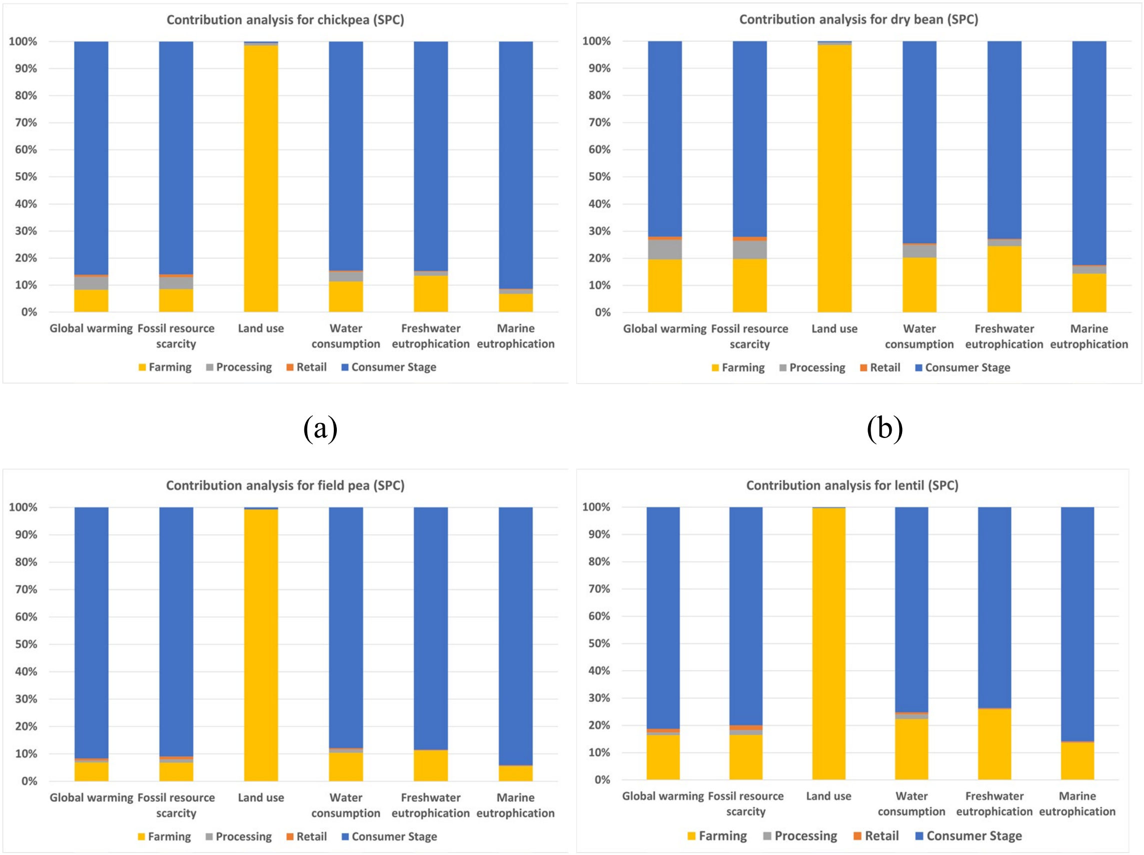
[4] Average of cooking times for green lentils, brown lentils, split red lentils, yellow lentils



(a) (b)

(c) (d)

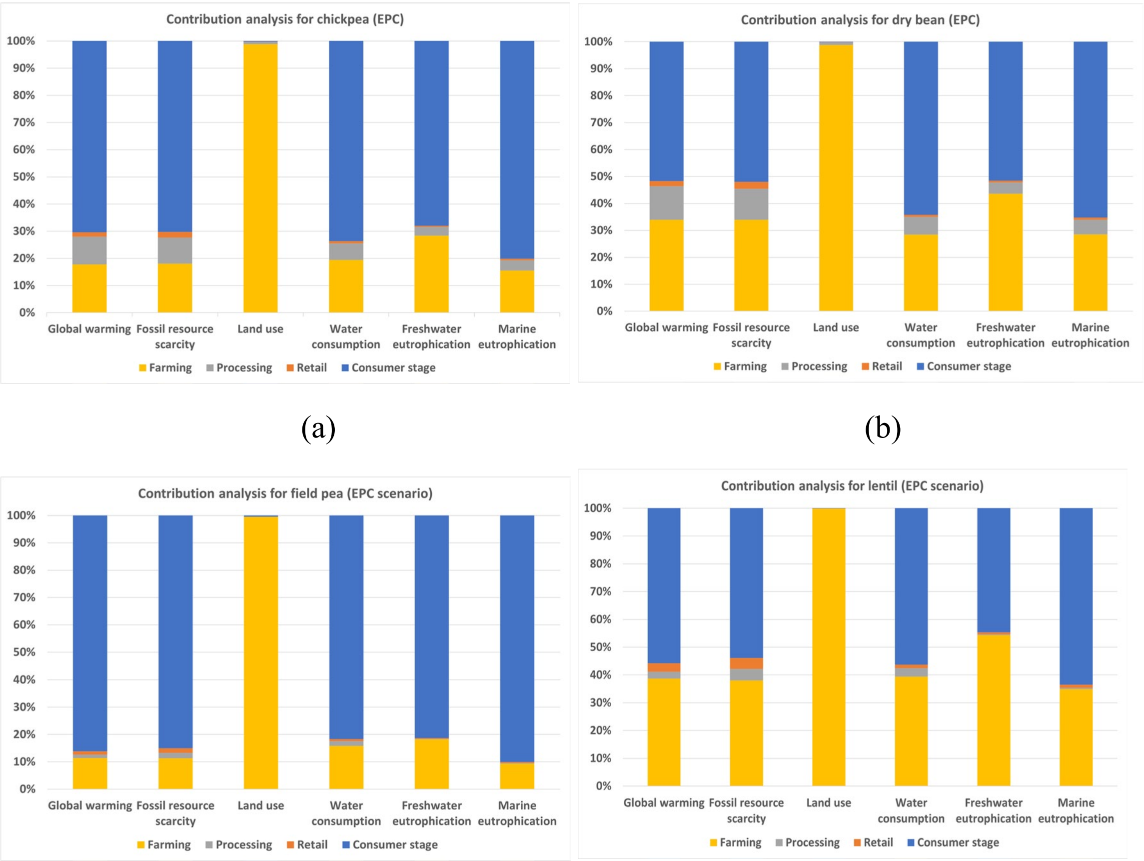
Figure A.1- Environmental impact associated with production and consumption of 60 g of pulses estimated for open vessel cooking (OVC) scenario for (a) fossil resource scarcity, (b) freshwater eutrophication, (c) marine eutrophication, and (d) water consumption. Overall, the environmental impact for these impact categories was the greatest for dry bean, followed by chickpea, field pea, and lentil. This was attributed to the differences in cooking time and nitrogen fertilizer requirements of pulse species. In general, longer cooking times resulted in higher electricity use and environmental impact as seen in figure (a).



(a) (b)

(c) (d)

Figure A.2- Results of contribution analysis for Stovetop Pressure Cooking (SPC) scenario, for 60 g of (a) chickpea, (b) dry bean, (c) field pea, and (d) lentil produced and consumed in the United States.



(a) (b)

(c) (d)

Figure A.3 – Results of contribution analysis for Electric Pressure Cooking (EPC) scenario, for 60 g of (a) chickpea, (b) dry bean, (c) field pea, and (d) lentil produced and consumed in the United States. The EPC only marginally decreased the contribution from consumer stage compared to OVC.

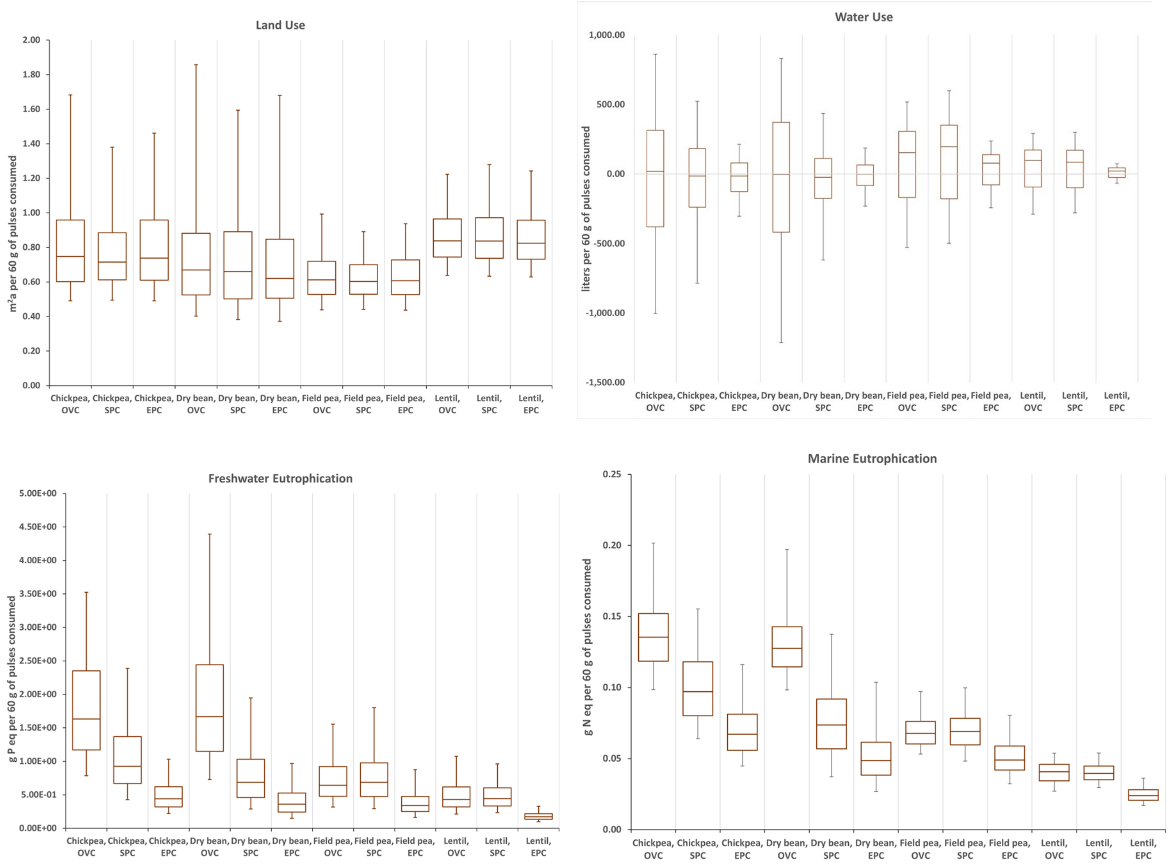


Figure A.4- Results of uncertainty analysis comparing the influence of cooking method on land use, water consumption, freshwater eutrophication, and marine eutrophication for 60 g of pulses cooked and consumed in the United States. Results for global warming potential and fossil resource scarcity are provided in the manuscript.

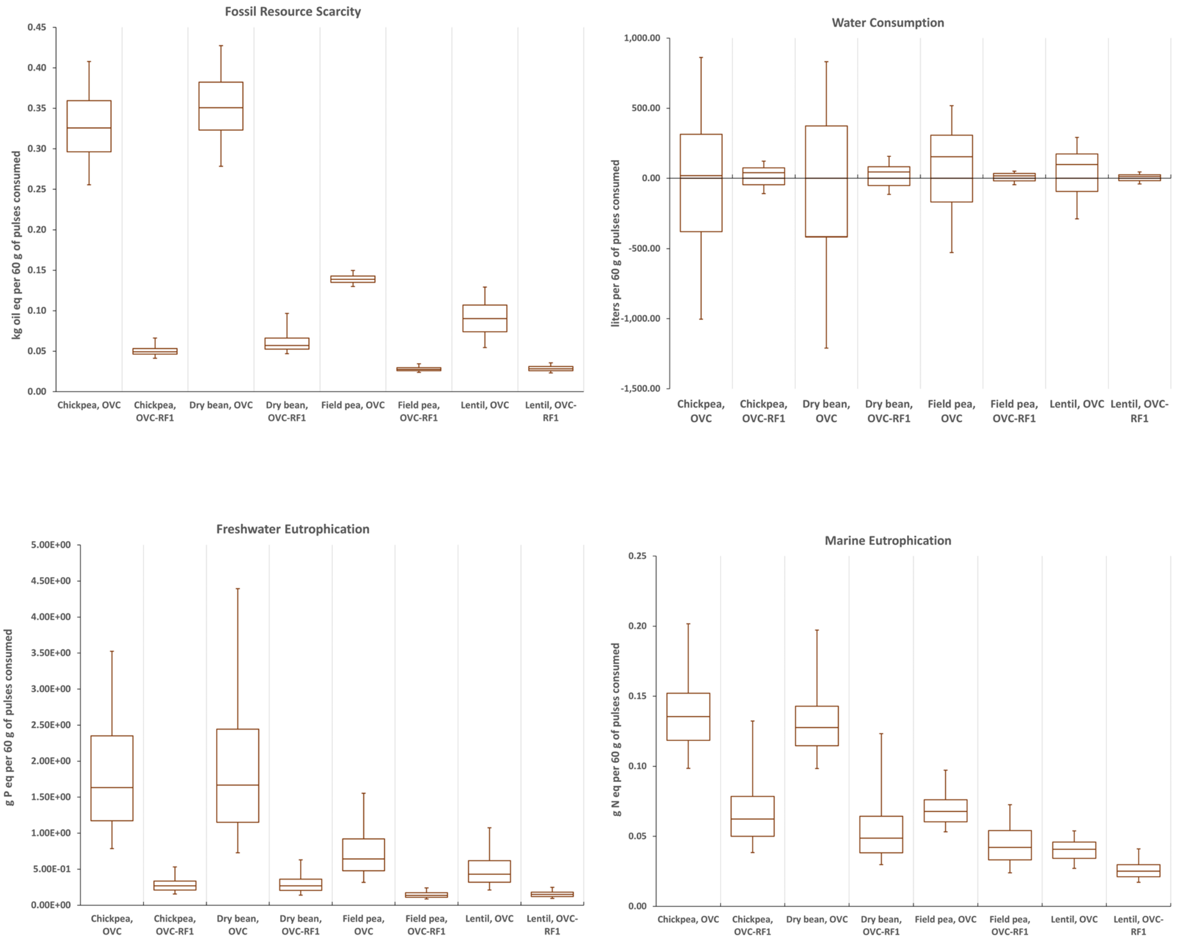
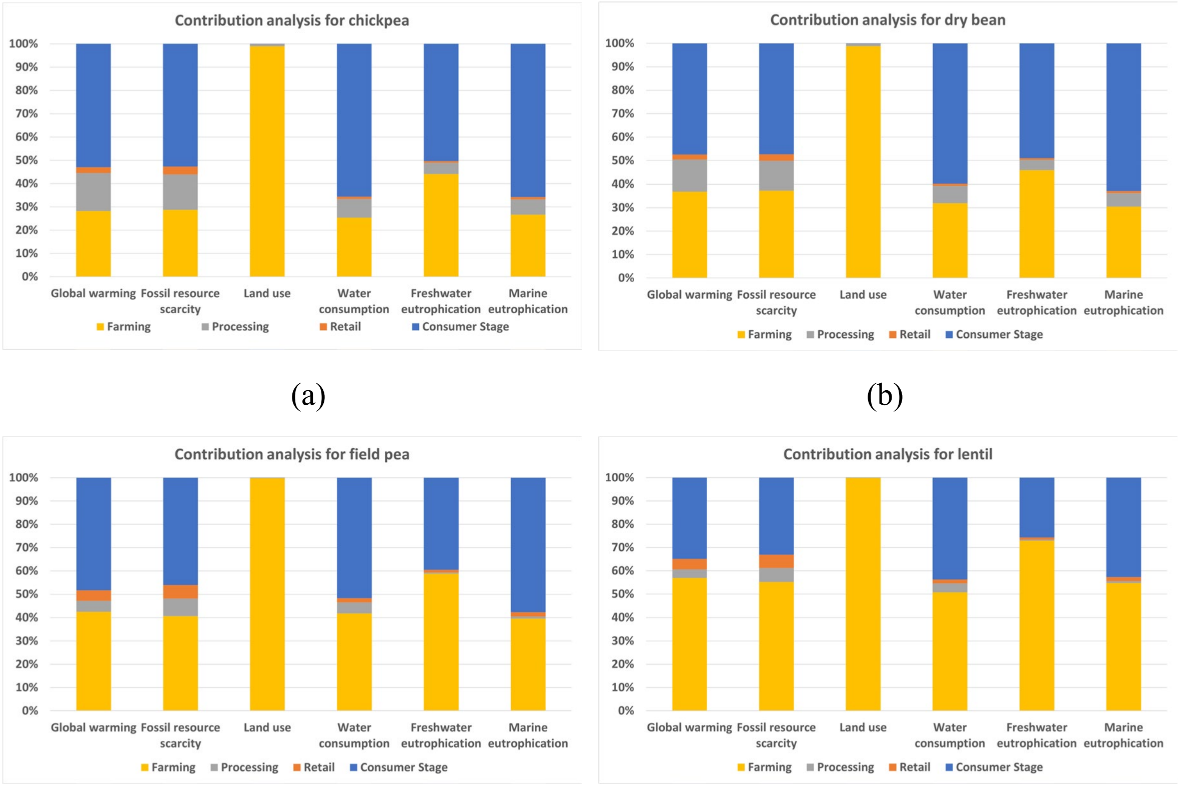


Figure A.5- Results of uncertainty analysis comparing the impact of cooking batch size on sustainability impact categories. The scenarios compared here are open vessel cooking with the reference flow (RF) of 60 g of pulses (OVC) and open vessel cooking with the RF of 1 kg of pulses (OVC-RF1). The functional unit for both scenarios was 60 g of pulses cooked and consumed in the United States. Cooking pulses in bulk (1kg per batch vs 60 g per batch) resulted in statistically significant reductions the environmental impact for fossil resource scarcity, freshwater eutrophication, and marine eutrophication. The changes to the mean values of water consumption observed for these scenarios were not statistically significant.



(a) (b)

(c) (d)

Figure A.6- Results of contribution analysis for OVC-RF1 scenario for 60 g of (a) chickpea, (b) dry bean, (c) field pea, and (d) lentil produced and consumed in the United States. A trade-off between contributions from the consumer and farming stages can be observed compared to other scenarios. Cooking 1 kg of pulses of pulses in a single batch decreased the contribution from the consumer stage for the function unit of 60 g. This trade-off between the consumer and farming stages was attributed to more efficient use of cooking-related electricity.

Figure A.7 Contribution analysis Cradle-to-farmgate impact

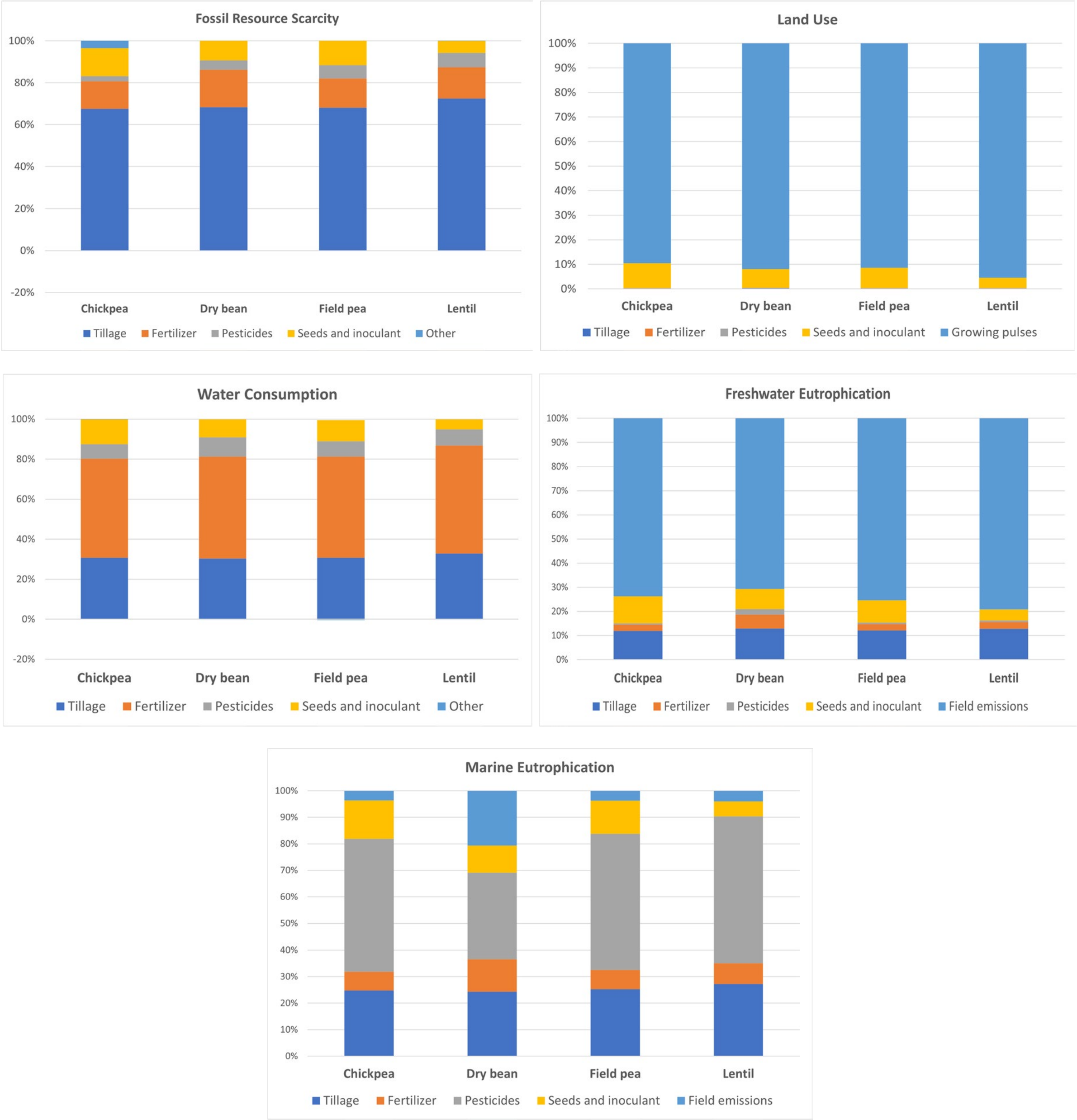


Figure A.7- Results of contribution analysis for environmental impact of 1 kg of pulses at the farmgate. The dominant contributors included tillage operations, fertilizers, pesticides, and production of seeds and inoculant. Field emissions was another contributor, primarily to GWP and freshwater eutrophication. Higher nitrogen fertilizer demand of dry bean increased the contribution of field emissions to its marine eutrophication score compared to other pulse species. However, in general, pesticide production and application dominated the marine eutrophication impact of pulses. Crop production and seed and inoculant production were responsible for 90 to 96 percent of land use impact of pulses.

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Appendix B – Supplementary material for Chapter 3

Table B.1- Factors used to disaggregate National American Industry Classification System (NAICS) sectors in Comprehensive Environmental Data Achieve (CEDA) into subsectors relevant for the study.

NAICS code	Sectors and subsectors	Disaggregation Factor, %
1111A0	**Oilseed farming[1,2,3]**	
	Soybean farming	92.59
	Other oilseed farming	7.40
1111B0	**Grain farming[4]**	
	Grain farming, other grains	98.07
	Dry beans	1.04
	Chickpea	0.40
	Dry edible peas	0.26
	Lentils	0.20
112300	**Poultry and egg production[5]**	
	Poultry Production	80.91
	Egg Production	19.08
115000	**Support activities for agriculture and forestry[2,7]**	
	Other support activities for agriculture and forestry	76.06
115114	Post-harvest crop activities (except cotton ginning)	23.93
	Post-harvest crop activities (except cotton ginning), other crops	59.43
	Post-harvest crop activities, dry pulses	1.14
	Post-harvest crop activities, nuts	9.45
	Post-harvest crop activities, fresh vegetables, dark green	3.18
	Post-harvest crop activities, fresh vegetables, red and orange	3.11
	Post-harvest crop activities, fresh vegetables, starchy	1.99
	Post-harvest crop activities, fresh vegetables, other	4.15
	Post-harvest crop activities, fresh fruits	17.50
311410	**Frozen food manufacturing[2, 7]**	
311411	Frozen Fruit, Juice, and Vegetable Manufacturing	37.24
	Frozen Vegetable Manufacturing, Dark Green	0.30
	Frozen Vegetable Manufacturing, Red and Orange	0.09
	Frozen Vegetable Manufacturing, Starchy	97.81
	Frozen Vegetable Manufacturing, Other	1.13
	Frozen Fruits Manufacturing	0.65
311412	Frozen Specialty Food Manufacturing	62.75

Table B.1 (contd.)- Factors used to disaggregate National American Industry Classification System (NAICS) sectors in Comprehensive Environmental Data Achieve (CEDA) into subsectors relevant for the study.

NAICS code	Sectors and subsectors	Disaggregation Factor, %
311420	**Fruit and vegetable canning, pickling, and drying**[2,7]	
	Vegetable canning, pickling, and drying, Dark Green	0.00
	Vegetable canning, pickling, and drying, Red and Orange	14.92
	Vegetable canning, pickling, and drying, Starchy	1.16
	Vegetable canning, pickling, and drying, Other	3.02
	Fruit canning, pickling, and drying	80.88
31151A	**Fluid milk and butter manufacturing**[8, 9, 10]	
	Fluid milk and butter manufacturing, dairy milk	99.94
	Fluid milk and butter manufacturing, soymilk	0.06
31161A	**Animal (except poultry) slaughtering, rendering, and processing**[2,7]	
	Animal (beef) slaughtering, rendering, and processing	75.35
	Animal (pork) slaughtering, rendering, and processing	24.64
311990	**All other food manufacturing**[6, 11]	
311990	All other food manufacturing	98.89
311991	Tofu manufacturing	1.11
325310	**Fertilizer manufacturing**	
	Nitrogen Fertilizer Manufacturing	52.39
	P2O5 Fertilizer Manufacturing	22.62
	K2O Fertilizer Manufacturing	24.98

Source for data used for disaggregation
[1] USDA-Economic Research Service (2019a), [2] USDA-National Agricultural Statistics Services (2018), [3] Schipanski et al. (2010), [4] USDA-National Agricultural Statistic Services (2019), [5] USDA-Economic Research Service (2019b), [6] U.S. Census Bureau (2021), [7] USDA-Economic Research Service (2020), USDA-Economic Research Services (2018), McCarthy (2019), Walmart Inc (2021a), Walmart Inc, 2021b, USDA-Economic Research Service, (2019c)

Table B.2- Retail prices, conversion factors for CEDA sectors used to convert retail prices to producer's prices, and producers' prices for various food groups

Food group	Retail Price, $/kg	CEDA Sector	Conversion Factor	Producers Price, $/kg
Fruits				
Fresh	5.43	Support activities for agriculture and forestry	1.00	5.43
Frozen	4.29	Frozen food manufacturing	0.88	3.79
Canned	3.69	Fruit and vegetable canning, pickling, and drying	0.86	3.18
Vegetables				
Dark green				
Fresh	4.55	Support activities for agriculture and forestry	1.00	4.55
Frozen	4.55	Frozen food manufacturing	0.88	4.01
Canned	2.41	Fruit and vegetable canning, pickling, and drying	0.86	2.07
Red and orange				
Fresh	3.02	Support activities for agriculture and forestry	1.00	3.02
Frozen	3.02	Frozen food manufacturing	0.88	2.66
Canned	2.43	Fruit and vegetable canning, pickling, and drying	0.86	2.09
Starchy				
Fresh	2.73	Support activities for agriculture and forestry	1.00	2.73
Frozen	2.73	Frozen food manufacturing	0.88	2.41
Canned	2.08	Fruit and vegetable canning, pickling, and drying	0.86	1.79
Other				
Fresh	4.29	Support activities for agriculture and forestry	1.00	4.29
Frozen	4.29	Frozen food manufacturing	0.88	3.79
Canned	3.05	Fruit and vegetable canning, pickling, and drying	0.86	2.62
Whole grains				
Bread and bakery product manufacturing	5.60	Bread and bakery product manufacturing	0.85	4.77
Frozen specialty food manufacturing	13.63	Frozen specialty food manufacturing	0.88	12.03
Cookie, crackers, and pasta manufacturing	5.60	Cookie, crackers, and pasta manufacturing	0.86	4.84
Breakfast cereal manufacturing	5.60	Breakfast cereal manufacturing	0.87	4.88

Table B.2 (contd.)- Retail prices, conversion factors for CEDA sectors used to convert retail prices to producer's prices, and producers' prices for various food groups

Food Group	Retail Price, $/kg	CEDA Sector	Conversion Factor	Producers Price, $/kg
Flour milling and malt manufacturing	3.04	Flour milling and malt manufacturing	0.83	2.52
All other food manufacturing	13.63	All other food manufacturing	0.84	11.50
Refined Grains				
Bread and bakery product manufacturing	4.84	Bread and bakery product manufacturing	0.85	4.13
Frozen specialty food manufacturing	6.28	Frozen specialty food manufacturing	0.88	5.55
Cookie, crackers, and pasta manufacturing	4.84	Cookie, crackers, and pasta manufacturing	0.86	4.19
Breakfast cereal manufacturing	4.84	Breakfast cereal manufacturing	0.87	4.22
Flour milling and malt manufacturing	2.26	Flour milling and malt manufacturing	0.83	1.88
All other food manufacturing	6.28	All other food manufacturing	0.84	5.30
Red meat, beef	13.18	Animal (except poultry) slaughtering, rendering, and processing	0.92	12.14
Red meat, pork	7.82	Animal (except poultry) slaughtering, rendering, and processing	0.92	7.20
Poultry	7.50	Poultry processing	0.94	7.02
Eggs	2.91	Poultry processing	0.94	2.72
Seafood	12.48	Seafood product preparation and packaging	0.71	8.81
Nuts and seeds				
Raw nuts and seeds	12.02	Tree nut farming	1.00	12.02
Processed nuts, seeds, and nut butter	4.47	Snack food manufacturing	0.86	3.86
Tofu	8.31	All other food manufacturing	0.84	7.01
Pulses	3.15	Support activities for agriculture and forestry	1.00	3.15

Table B.2 (contd.)- Retail prices, conversion factors for CEDA sectors used to convert retail prices to producer's prices, and producers' prices for various food groups

Food Group	Retail Price, $/kg	CEDA Sectors	Conversion Factors	Producers Price, $/kg
Dairy				
Fluid milk	1.15	Fluid milk and butter manufacturing, dairy milk	0.90	1.04
Cheese	8.24	Cheese manufacturing	0.89	7.32
Yogurt	4.35	Fluid milk and butter manufacturing, dairy milk	0.90	3.92
Frozen dairy products	7.11	Ice cream and frozen dessert manufacturing	0.80	5.71
Evaporated and condensed milk	3.34	Dry, condensed, and evaporated dairy product manufacturing	0.78	2.62
Dry milk	10.44	Dry, condensed, and evaporated dairy product manufacturing	0.78	8.19
Soymilk	1.40	Fluid milk and butter manufacturing	0.90	1.26
Oils	7.37	Fats and oils refining and blending	0.93	6.84
Fats	5.91	Fats and oils refining and blending	0.93	5.49
Sugars	2.64	Sugar cane mills and refining	0.87	2.28

Table B.3 Grain consumption from various sources in the diets of adults (19 years and older) (Albertson et al. (2015) mapped to CEDA database

Product	Consumption, %		CEDA Sector
	Whole Grain	Refined Grains	
Yeast bread, rolls	26.3	38.6	311810, Bread and bakery product manufacturing
Grain mixture, frozen plate meals, soups, meat substitute	25.4	2.4	311412, Frozen specialty food manufacturing
All other foods (meat, poultry, fish mixtures, including	11.8	1.1	311810, Bread and bakery product manufacturing
Crackers and non-popcorn salty snacks from grains	8.4	12.0	311820, Cookie, crackers, and pasta manufacturing
Cakes, cookies, pies, pastries	8.6	3.2	311810, Bread and bakery product manufacturing
Quick breads	6.3	1.0	311810, Bread and bakery product manufacturing
Pastas, macaroni, rice	4.5	5.9	311810, Bread and bakery product manufacturing
Ready to eat cereals	4.3	18.6	311230, Breakfast cereal manufacturing
Pancakes, waffles, French toast, crepes	1.5	1.1	311210, Flour milling and malt manufacturing
Oatmeal	1.5	10.6	311230, Breakfast cereal manufacturing
Popcorn	0.8	5.3	311990, All other food manufacturing
Other cooked cereals	0.6	0.2	311230, Breakfast cereal manufacturing

Table B.4- Average annual energy and refrigerant consumption intensities used to estimate and allocate energy consumption to food groups at the retail sector

Parameter	Value
2018 median supermarket area[1], m^2	3940.48
Number of supermarkets[1]	38307.00
Commercial refrigeration charge size[2], kg	1587.57
Annual commercial refrigeration leak rate[2]	25.00%
Typical commercial refrigerant used[2]	R-404A
Average electricity use intensity[3], $kWh/m^2/year$	538.20
Average natural gas used intensity[3], $m^3/m^2/year$	15.24
Refrigeration electricity demand[4]	43.00%
Overhead electricity demand[4]	55.00%
Overhead natural gas demand[4]	87.00%
Water use[5], $L/m^2/year$	2876.66
Total sale of grocery[6]	81.00%
Total sale of shelf stable food[6]	32.00%
Total sale of refrigerated food[6]	49.00%

[1] Food Marketing Institute (2021), [2] U.S. Environmental Protection Agency (2011), [3] ENERGY STAR (2021a), [4] U.S. Environmental Protection Agency (2008), [5] Aquacraft, Inc. Water Engineering and Management (2004), [6] Chanil et al (2019)

Table B.5- Data used to estimate and allocated residential resource use to food groups

Parameters	Value
Total electricity use[1], kWh/year	4288.00
Electricity use for refrigeration[1], kWh/year	302.00
Electricity use for cooking[1], kWh/year	96.40
Electricity use for microwaves[1], kWh/year	49.20
Electricity use for dishwashers[1], kWh/year	45.20
Natural gas for cooking[1], $m^3/year$	0.03
Propane use for cooking[1], MJ/year	1320.93
Dishwasher water consumption[2], L/day	12.16
Soap[3], g/day	25.00
Average distance to grocery store[4], km	5.32
Number of trips to grocery store per week[5]	1.60

[1] U.S. EIA (2015), [2] U.S. Environmental Protection Agency (2011), [3] ENERGY STAR (2021b), [4] USDA Economic Research Service (2015), Food Marketing Institute (2019)

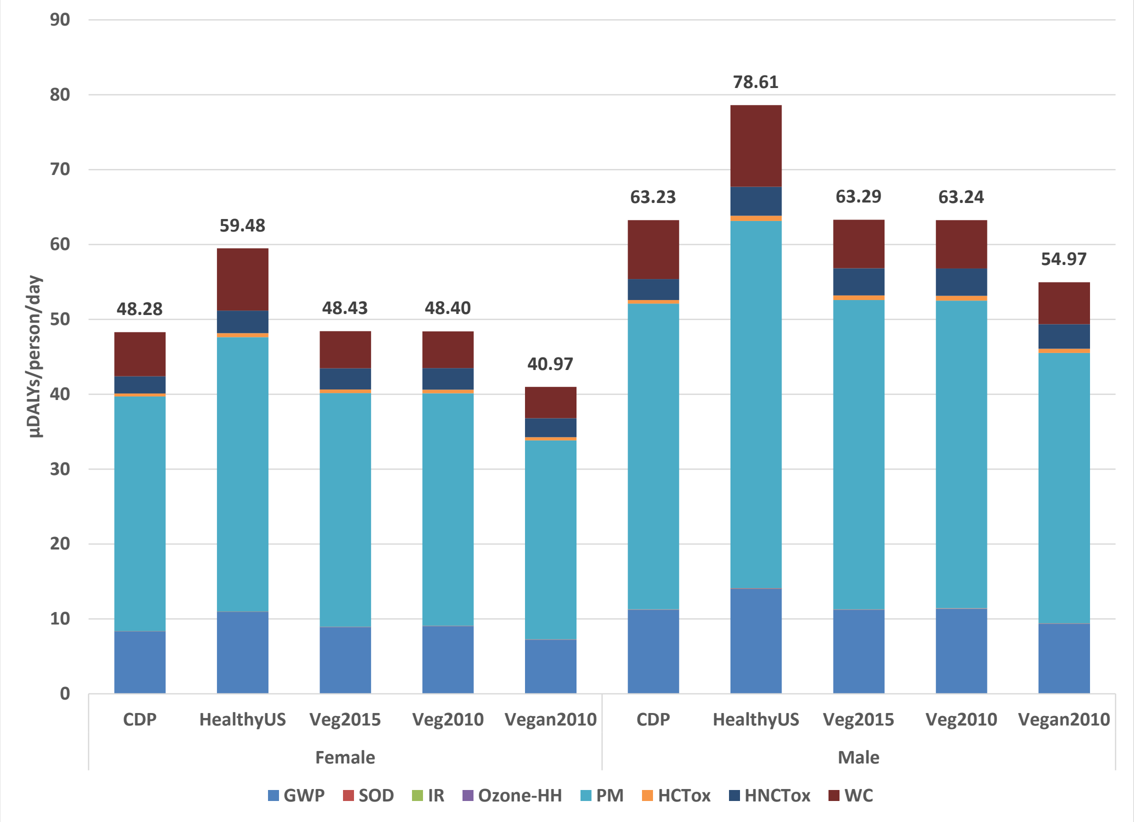

Figure B.1- Contribution from environmental emissions to emissions-related adverse health impact of current and recommended dietary patterns.

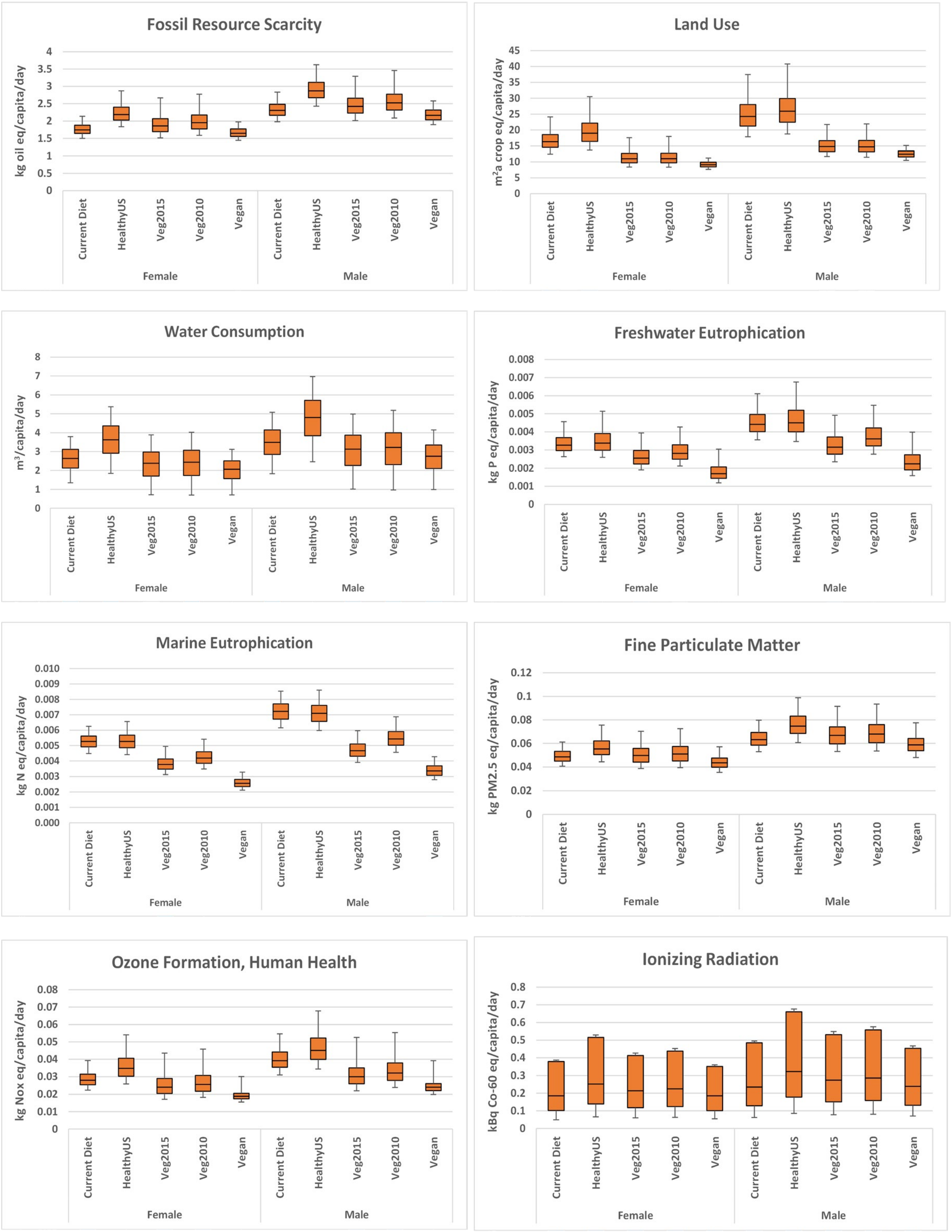

Figure B.2- Results of uncertainty analysis performed using 1000 Monte Carlo Simulations for midpoint categories

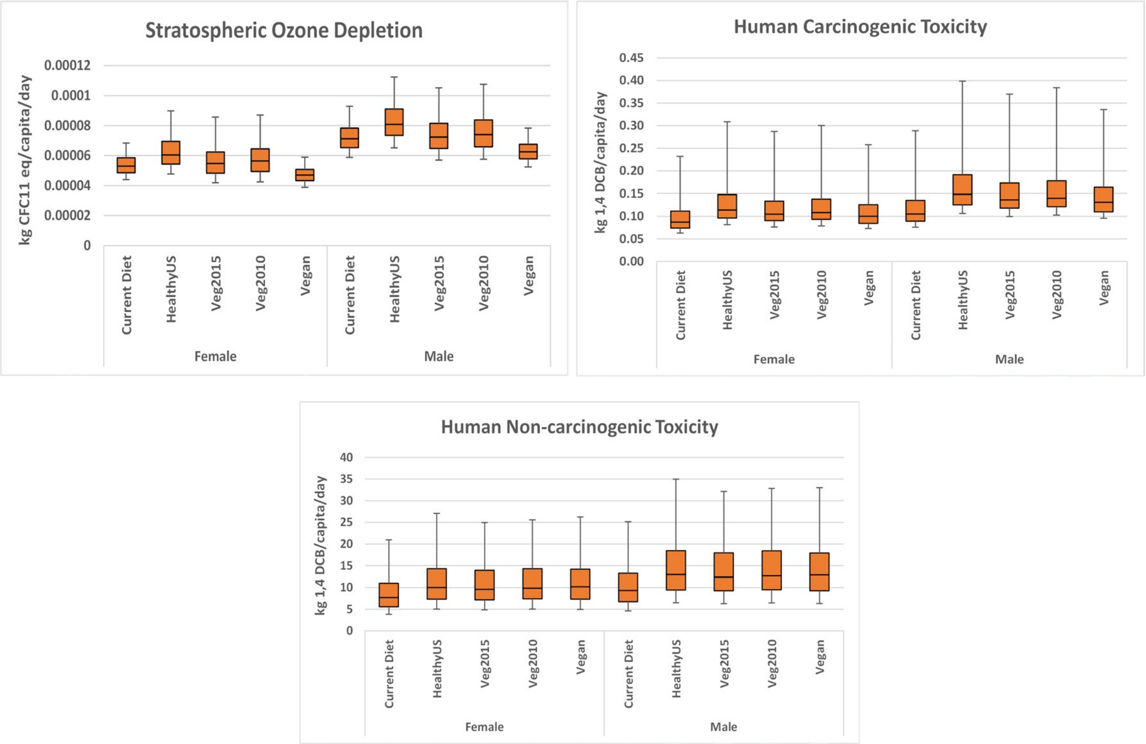

Figure B.2 (continued)- Results for uncertainty analysis conducted using 1000 Monte Carlo Simulations for midpoint impact categories

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Appendix C – Supplementary material for Chapter 4

Table C.1- Nutrient profile of various pulse crop species/varieties used to estimate average amino acid concentration in pulses. Nutrient concentrations are presented for 100 g of pulses

Nutrients[1]	Adzuki beans	Black beans	French beans	Navy beans	Pink beans	White beans	Yellow beans	Hyacinth beans	Mung beans	Mungo beans
FDC ID	**173727**	**173734**	**173738**	**173745**	**173748**	**175202**	**173751**	**175210**	**174256**	**174259**
Energy, kcal	329.00	341.00	343.00	337.00	343.00	333.00	345.00	344.00	347.00	341.00
Protein, g	19.90	21.60	18.80	22.30	21.00	23.40	22.00	23.90	23.90	25.20
Tryptophan, g	0.19	0.25	0.22	0.25	0.25	0.28	0.26	0.20	0.26	0.26
Threonine, g	0.67	0.91	0.79	0.71	0.88	0.98	0.93	0.92	0.78	0.88
Isoleucine, g	0.79	0.95	0.83	0.95	0.92	1.03	0.97	1.14	1.01	1.29
Leucine, g	0.17	1.72	1.50	1.72	1.67	1.86	1.76	2.03	1.85	2.09
Lysine, g	0.15	1.48	1.29	1.28	1.44	1.60	1.51	1.63	1.66	1.67
Methionine, g	0.21	0.33	0.28	0.27	0.31	0.35	0.33	0.19	0.29	0.37
Cystine, g	0.18	0.24	0.21	0.19	0.22	0.25	0.24	0.28	0.21	0.23
Phenylalanine, g	1.05	1.17	1.02	1.16	1.13	1.26	1.19	1.20	1.44	1.47
Tyrosine, g	0.59	0.61	0.53	0.48	0.59	0.66	0.62	0.85	0.71	0.78
Valine, g	1.02	1.13	0.98	1.24	1.10	1.22	1.15	1.24	1.24	1.42
Arginine, g	1.28	1.34	1.16	1.02	1.30	1.45	1.36	1.76	1.67	1.64
Histidine, g	0.52	0.60	0.52	0.50	0.58	0.65	0.61	0.68	0.69	0.71
Alanine, g	1.16	0.91	0.79	0.91	0.88	0.98	0.92	1.07	1.05	1.08
Zinc, mg	5.04	3.65	1.90	3.65	2.55	3.67	2.83	9.30	2.68	3.35
Iron, mg	4.98	5.02	3.40	5.49	6.77	10.40	7.01	5.10	6.74	7.57

[1] Source- Food Data Central (USDA-Agricultural Research Services, 2022). Data can be searched on Food Data Central's website using FDC ID

Table C.1 (contd.)- Nutrient profile of various pulse crop species/varieties used to estimate average amino acid concentration in pulses. Nutrient concentrations are presented for 100 g of pulses

Nutrients[1]	Winged beans	Yard long beans	Black turtle beans	Cranberry (roman) beans	Red kidney beans	Small white beans	Fava beans	Lima beans, large	Kidney beans, all types	Kidney beans, California red
FDC ID	**174283**	**174281**	**175186**	**175189**	**173744**	**173749**	**1175205**	**174252**	**175193**	**173742**
Energy, kcal	409.00	347.00	339.00	335.00	337.00	336.00	341.00	338.00	333.00	330.00
Protein, g	29.60	24.30	21.20	23.00	22.50	21.10	26.10	21.50	23.60	24.40
Tryptophan, g	0.76	0.30	0.25	0.27	0.27	0.25	0.25	0.25	0.28	0.29
Threonine, g	1.18	0.93	0.89	0.97	0.95	0.89	0.93	0.93	0.99	1.03
Isoleucine, g	1.47	0.99	0.94	1.02	1.00	0.93	1.05	1.13	1.04	1.08
Leucine, g	2.50	1.86	1.70	1.84	1.80	1.68	1.96	1.85	1.88	1.95
Lysine, g	2.14	1.65	1.46	1.58	1.55	1.45	1.67	1.44	1.62	1.67
Methionine, g	0.36	0.35	0.32	0.35	0.34	0.32	0.21	0.27	0.36	0.37
Cystine, g	0.55	0.27	0.23	0.25	0.25	0.23	0.33	0.24	0.26	0.27
Phenylalanine, g	1.43	1.42	1.15	1.24	1.22	1.14	1.10	1.24	1.28	1.32
Tyrosine, g	1.46	0.79	0.60	0.65	0.63	0.59	0.83	0.76	0.66	0.69
Valine, g	1.53	1.16	1.11	1.20	1.18	1.10	1.16	1.29	1.23	1.28
Arginine, g	1.89	1.68	1.32	1.43	1.40	1.31	2.41	1.32	1.46	1.51
Histidine, g	0.79	0.76	0.59	0.64	0.63	0.59	0.66	0.66	0.66	0.68
Alanine, g	1.04	1.11	0.89	0.97	0.95	0.89	1.07	1.10	0.99	1.02
Zinc, mg	4.48	3.50	2.20	3.63	2.79	2.81	3.14	2.83	2.79	2.55
Iron, mg	13.40	8.61	8.70	5.00	6.69	7.73	6.70	7.51	8.20	9.35

[1] Source- Food Data Central (USDA-Agricultural Research Services, 2022). Data can be searched on Food Data Central's website using FDC ID

Table C.1 (contd.)- Nutrient profile of various pulse crop species/varieties used to estimate average amino acid concentration in pulses. Nutrient concentrations are presented for 100 g of pulses

Nutrient[1]	Kidney beans, royal red	Chickpeas	Lima beans, baby	Pinto beans	Great northern beans	Green peas	Pigeon pea (red gram)	Lentils	Lentils, pink or red
FDC ID	**175196**	**173756**	**174255**	**175199**	**175190**	**172428**	**172436**	**172420**	**174284**
Energy, kcal	329.00	378.00	335.00	347.00	339.00	364.00	343.00	352.00	358.00
Protein, g	25.30	20.50	20.60	21.40	21.90	23.10	21.70	24.60	23.90
Tryptophan, g	0.30	0.20	0.24	0.24	0.26	0.16	0.21	0.22	0.22
Threonine, g	1.07	0.77	0.89	0.81	0.92	0.81	0.77	0.88	0.90
Isoleucine, g	1.12	0.88	1.08	0.87	0.97	0.98	0.79	1.06	1.08
Leucine, g	2.02	1.46	1.78	1.56	1.74	1.68	1.55	1.79	1.81
Lysine, g	1.74	1.38	1.38	1.36	1.50	1.77	1.52	1.72	1.74
Methionine, g	0.38	0.27	0.26	0.26	0.33	0.20	0.24	0.21	0.21
Cystine, g	0.28	0.28	0.23	0.19	0.24	0.27	0.25	0.32	0.33
Phenylalanine, g	1.37	1.10	1.19	1.10	1.18	1.15	1.86	1.22	1.23
Tyrosine, g	0.71	0.51	0.73	0.43	0.62	0.52	0.54	0.66	0.67
Valine, g	1.32	0.87	1.24	1.00	1.14	1.04	0.94	1.22	1.24
Arginine, g	1.57	1.94	1.26	1.10	1.35	1.90	1.30	1.90	1.93
Histidine, g	0.71	0.57	0.63	0.56	0.61	0.59	0.77	0.69	0.70
Alanine, g	1.06	0.88	1.05	0.87	0.92	1.05	0.97	1.03	1.04
Zinc, mg	2.66	2.76	2.60	2.28	2.31	3.49	2.76	3.27	3.60
Iron, mg	8.70	4.31	6.19	5.07	5.47	4.73	5.23	6.51	7.39

[1] Source- Food Data Central (USDA-Agricultural Research Services, 2022). Data can be searched on Food Data Central’s website using FDC ID

Table C.2- Nutrient profile of various varieties of rice used to estimate average amino acids concentration. Nutrient concentrations are presented for 100 g of pulses

Nutrient[1]	Rice, white, medium grain, enriched	Rice, white, medium-grain, unenriched	Rice, white, short-grain, unenriched	Rice, white, long-grain, regular, enriched	Rice, white, long-grain, regular, unenriched	Rice, brown, long-grain, raw	Rice, brown, medium grain	Wild rice, raw
FDC ID	**168879**	**169760**	**168931**	**168877**	**169756**	**169703**	**169706**	**169726**
Energy, kcal	360.00	360.00	358.00	365.00	365.00	367.00	362.00	357.00
Protein, g	6.61	6.61	6.50	7.13	7.1	7.54	7.50	14.70
Tryptophan, g	0.08	0.08	0.07	0.08	0.08	0.10	0.10	0.18
Threonine, g	0.24	0.23	0.23	0.25	0.25	0.29	0.28	0.47
Isoleucine, g	0.28	0.28	0.28	0.31	0.31	0.34	0.32	0.62
Leucine, g	0.55	0.55	0.54	0.59	0.59	0.66	0.62	1.02
Lysine, g	0.24	0.24	0.23	0.26	0.26	0.30	0.29	0.63
Methionine, g	0.15	0.15	0.15	0.17	0.17	0.18	0.17	0.44
Cystine, g	0.13	0.13	0.13	0.15	0.15	0.10	0.09	0.17
Phenylalanine, g	0.35	0.35	0.34	0.38	0.38	0.41	0.39	0.72
Tyrosine, g	0.22	0.22	0.21	0.24	0.24	0.30	0.28	0.62
Valine, g	0.40	0.40	0.39	0.43	0.43	0.47	0.44	0.86
Arginine, g	0.55	0.55	0.54	0.59	0.59	0.60	0.66	1.14
Histidine, g	0.15	0.15	0.15	0.17	0.17	0.20	0.19	0.38
Alanine, g	0.38	0.38	0.38	0.41	0.41	0.46	0.437	0.82
Zinc, mg	1.16	1.16	1.10	1.09	1.09	2.13	2.02	5.96
Iron, mg	4.36	0.80	0.80	4.31	0.8	1.29	1.8	1.96

[1] Source- Food Data Central (USDA-Agricultural Research Services, 2022). Data can be searched on Food Data Central's website using FDC ID

References

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