IMPLICATIONS OF FUTURE US DIET SCENARIOS ON GREENHOUSE GAS EMISSIONS

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January 13, 2020

Document Description

IMPLICATIONS OF FUTURE US DIET SCENARIOS ON GREENHOUSE GAS EMISSIONS
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Center for Sustainable Systems, Report No. CSS20-01
University of Michigan, Ann Arbor, Michigan
January 13, 2020
30 pp., 10 tables, 5 figures, 2 appendices

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This document is available online at: http://css.umich.edu/publication/implications-future-us-diet-scenarios-greenhouse-gas-emissions

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Executive Summary

Linkages between diet and environmental impact have been repeatedly emphasized at the global and national level, with an indication that shifts in diet, typically toward more plant-based foods, can lead to significant reduction in environmental impact. In this study, we explore the effect on food system greenhouse gas emissions (GHGE) of a hypothetical reduction in the consumption of animal-based foods in the US diet and a replacement with plant-based foods.

USDA's Loss Adjusted Food Availability (LAFA) dataset, a top-down estimate of the per capita consumption of commodity foods in the US, is used to represent the baseline, or current, US diet. Greenhouse gas emission factors previously compiled from life cycle assessment literature were linked to these commodity foods to estimate the per capita GHGE associated with agricultural production of the average diet. A number of dietary scenarios projected to 2030 were then developed:

1. The baseline average diet remains unchanged to 2030
2. Meat and poultry consumption increases per USDA projections
3. Consumption of animal-based foods (red meat, poultry, fish/seafood, eggs, dairy, and animal based fats) decreases by 50%, and is substituted with plant-based foods
4. Same as scenario 3, but beef decreases by 90%, instead of 50%.

The total emissions associated with producing the average US diet amounts to 5.0 kg CO_2 eq. per person per day. Whereas red meat (beef, pork, lamb) represents 9% of the calories available from this diet, it contributes 47% of the GHGE. All animal-based foods combined (red meat, poultry, fish/seafood, eggs, dairy, and animal based fats) represent 82% of the baseline diet GHGE. According to LAFA data, the average American consumed 133 pounds of red meat and poultry in 2016. USDA projects slight increases in per capita red meat and poultry consumption in the US in 2028 (scenario 2); assuming other foods unchanged, this raises the carbon footprint to 5.14 kg CO_2 eq. per person per day.

Cutting the intake of all animal-based foods by half and replacing with equivalent quantities of plant-based foods (scenario 3) results in a 35% decrease in GHGE from the baseline, to 3.3 kg CO_2 eq per person per day. Under this scenario 3, red meat represents 36% of the total emissions. Further reducing consumption of beef to only 10% of the baseline value, and subsequent replacement with plant-based proteins (scenario 4), cuts the diet-related emissions to 2.4 kg CO_2 eq per capita per day, a 51 % decrease from the baseline diet. Under this final scenario 4, the average American consumes 50.1 pounds of meat and poultry per year.

Using population projections from the US Census Bureau, an unchanged diet would result in 646 million metric tonnes CO_2 eq. (MMT) in 2030, whereas scenario 3 – replacing 50% of all animal-based foods with plant-based alternatives – leads to 224 MMT less emissions per year in 2030, a reduction equivalent to the annual emissions of 47.5 million of today's average passenger vehicles. If we assume a linear transition from the 2016 diet to 2030 projections, this target of 50% substitution results in an estimated cumulative reduction of 1634 MMT. By further replacing 90% of beef, the cumulative emission reduction increases to 2408 MMT.

Although reliant on a number of simplifying assumptions, this diet projection exercise emphasizes the important role that changes in diet can play in climate action. An annual emission reduction of 224 MMT represents 24% of the reduction from 2017 emissions required to meet the US Intended Nationally

Determined Contribution to the UN Framework Convention on Climate Change. Recognition that such sizable reductions are possible *without* complete elimination of animal-based foods from the diet can make diet shift strategy more palatable. Such changes, however, will require the concerted efforts of policymakers, the food industry and consumers. The projection scenarios presented here point to the urgency of such efforts, as decisions made now will have a cumulative impact over the next decade.

1. Introduction

Food in the Anthropocene has been heralded as one of the greatest health and environmental challenges of the 21st century (Willett et al. 2019). Food production is an important contributor to a range of pressing environmental issues including climate change, biodiversity loss, land and water scarcity, and water pollution. Linkages between diet and environmental impact have been repeatedly emphasized at the global and national level, with indication that shifts in diet, typically toward more plant-based foods, can lead to significant reductions in impact (Tilman and Clark 2014; Hallstrom et al. 2015; Kim et al. 2019). Further, a number studies indicate that global shifts in diets that reduce foods from animal sources will likely be necessary in order to meet climate action targets (Bajželj et al. 2014; Hedenus et al. 2014; Springmann et al. 2018a).

Despite decades of raising alarm from the scientific community, insufficient progress has been made to reduce global greenhouse gas emissions (GHGE), and prompt reductions from nearly all sectors of society are now seen as necessary to avoid catastrophic climate changes (Ripple et al. 2019). The US is the second largest GHG emitting country, representing 13% of global emissions. According to recent UNEP assessments, current US policies are projected to fall short of achieving unconditional Nationally Determined Contributions by at least 15% in 2030, the largest projected underachievement of G20 nations (UNEP 2019). Agriculture is often cited as being a small contributor to total US emissions (e.g., agricultural activities were 8% of total US GHGE in 2017) as it is dwarfed by large transportation, energy and other industrial sectors. However, agriculture represents 38% of anthropogenic methane emissions in the US, with 36% originating from livestock (enteric fermentation and manure management) (US EPA 2019b). Targeting short-lived greenhouse gases such as methane is seen as an important near-term climate action strategy in order to reduce the damage due to climate change over the next few decades and to slow climate feedback loops (Shindell et al. 2017). Therefore, addressing contributions from food and agriculture, particularly the amount of animal-based foods in the US diet, can be seen as an urgent short-term goal.

There have been repeated efforts in recent years to evaluate the GHGE of diets in the US (Heller and Keoleian 2015; Tom et al. 2016; Heller et al. 2018; Boehm et al. 2019; Hitaj et al. 2019). While these studies vary in methodological approaches and come to somewhat different conclusions on the implications of a shift to currently recommended dietary patterns, they all point to a significant contribution from animal-based foods, and in particular foods from ruminant animals including beef and dairy.

In this study, we explore the implications to food system GHGE from a hypothetical reduction in consumption of animal based foods and a replacement with plant-based foods from corresponding food categories. We use USDA's Loss Adjusted Food Availability (LAFA) dataset as a proxy for the commodity foods consumed in the current US diet. These commodity foods are linked to GHG emission factors previously compiled from life cycle assessment literature (Heller et al. 2018). Baseline per capita diet-related GHGE are then determined using LAFA data for 2016, and in the status quo scenario, this diet is assumed unchanged through 2030. A number of diet shift scenarios are then projected to 2030 and the resulting changes in GHGE are calculated. Implications of the assumptions necessary in this exercise are addressed in the discussion section.

2. __Methods__

2.1. Defining baseline diet

USDA's Loss Adjusted Food Availability (LAFA) data for 2016 were used as the baseline for this study (USDA ERS 2019). The food availability series measures the use of basic food commodities (e.g., wheat, beef, fruit, and vegetables) by tracking their "disappearance" in the U.S. marketplace. For most commodities, the available supply is the sum of production, imports and beginning stocks, minus nonfood use (feed and seed, industrial uses), exports, and ending stocks for a given calendar year. In the LAFA data series, the food availability data for 208 commodities are modified by percent loss assumptions at the primary, retail/institution, and consumer levels. Retail losses include dented cans, unpurchased holiday foods, spoilage, and the culling of blemished or misshaped foods. Consumer losses include spoilage, cooking shrinkage, and plate waste. Note that USDA estimates report only food losses and do not differentiate between wastes (such as plate scraps) that could be avoided through behavioral change and losses (such as moisture losses during cooking) that are largely unavoidable. This should not affect the total diet carbon footprint (as the same quantity of farm-level foods are needed regardless of whether weight losses are from cooking or plate waste) but it should be considered in interpreting the proportion from food loss/waste.

For select foods in the LAFA series, data for 2016 were not available due to terminations of underlying data sources or other reasons. In these cases, the most recently available year was used as a proxy, as detailed in Table 1.

Table 1. Food Commodities requiring proxy values from previous years.

Food commodity	Data year used as proxy for 2016 per capita availability
Canned salmon frozen plums and prunes	2015
Rice Margarine Lard edible beef tallow shortening salad and cooking oils other edible fats and oils	2010
light cream	2006
dried pears	2005
fat share of half and half heavy cream	2001

2.2. GHG Emission Factors

LAFA food commodities were linked with greenhouse gas emission factors (kg CO_2 eq/kg; 100-year Global Warming Potential basis) derived from life cycle assessment literature and compiled in the dataFIELD database (Heller et al. 2018). In a select few commodity entries without direct dataFIELD linkages, additional literature values were used to estimate the emissions associated with these

commodities. Methods and specific linkages are detailed in Appendix A. These data represent emissions associated with "average" agricultural production of commodities or, in the case of minimally processed commodities including flours, oils, sugars, dairy products, juices, and dried fruit/vegetables, include processing. Downstream food processing, distribution, retailing, food service or consumption stages are not included in the carbon footprint estimates. Note that in the absence of consistent, regionally specific datasets on environmental impacts of agricultural production, it is common practice in the current literature on diet-related environmental impacts to utilize generic representative data.

Concerted effort was made in the linking process to assure that the weight basis properly corresponded between LAFA and emission factor data. This pertained primarily to the inclusion or exclusion of inedible portions (rinds, peels, cores, bones, etc.). Further, to assure proper accounting for food losses, the "linkage point" (i.e., the starting point in food loss chain for connecting to environmental impact data) needed to be adjusted by LAFA entry. In most cases, the linkage point was "retail weight" as the losses from the primary to retail level were not relevant or were already accounted for in GHG values (e.g., removal of bones and other inedibles for flesh foods). However, for canned and frozen fruits and vegetables, linkages are made at the primary level. In these cases, losses from primary to retail are assumed to represent losses during processing, and since emission factors represent the whole food at farm gate, these losses should be included.

Additional linkage assignments worth noting include:

a) The emission factor used for beef accounts for an estimated 19.5% of the US beef supply originating from dairy herds (Rotz et al. 2019) and is adjusted accordingly to represent the (typically) lower carbon footprint of beef from dairy [19.5%*19.0 + 80.5%*33.1 = 30.4 kg CO_2eq/kg boneless beef].
b) All fluid milk, regardless of fat content or flavored, was assigned the same emission factor value.
c) All cheeses were assigned the same emission factor value.
d) Animal-based fats (lard, tallow) were assigned the same emission factor as the corresponding meat.
e) Frozen and canned fruits and vegetables are represented by the fresh fruit/vegetable and therefore do not include emissions associated with the freezing or canning process.

2.3. Scenario definitions and development

Using the 2016 LAFA data as the baseline, scenarios for projected diets in 2030 were developed as summarized in Table 2. The development of scenarios 2, 3 and 4 is described in detail in the following sections. After establishing projected national average dietary patterns under each scenario, associated annual per capita emissions were calculated by multiplying commodity intake by the corresponding emission factor and summing across all foods. Note that while the developed scenarios contain similar quantities of macronutrients compared to the baseline, they have not been optimized or evaluated for complete nutritional adequacy or health.

Table 2. Summary of diet scenarios projected to 2030

Scenario #	Scenario name	Description of 2030 diet
Scenario 1	Baseline / status quo	2016 baseline diet projected to 2030 with no changes in per capita consumption
Scenario 2	USDA meat projections	per capita red meat and poultry consumption based on USDA macroeconomic projections; no changes in other foods
Scenario 3	50% animal reduction	50% reduction in the baseline per capita weight consumption of all animal-based foods in the diet, increasing the amount of legumes, soy products and nuts to match the baseline diet ounce equivalents of protein foods, adding soy milk to match the baseline diet cup equivalents of dairy, and increasing plant based fats to make up for reduced animal-based fats.
Scenario 4	50% animal / 90% beef reduction	Same as scenario 3, but with beef consumption reduced by 90% of the baseline weight consumption

2.3.1. Scenario 2 (USDA meat projections)

USDA, through an Interagency Agricultural Projections Committee, provides long-term projections for the agricultural sector, the most recent extending to 2028 (USDA 2019b). Projections are based on specific assumptions about the macroeconomic behaviors, agricultural and trade policies, the weather, and international developments. The most recent report offers per capita red meat and poultry consumption projections for the US population, which are based on the above modeling assumptions leading to decreasing prices, rising production and strong per capita consumption supported by moderate domestic GDP growth. Note that while the USDA Agricultural Projections report covers most major commodities, livestock (meat) is the only commodity reported directly in terms of per capita consumption, and information necessary to assess per capita consumption of other commodities is not provided. Therefore, scenario 2 considers only the changes in red meat and poultry consumption presented by this USDA report.

"Retail weight" per capita red meat and poultry consumption in 2028 was taken from Table 17 of (USDA 2019b). In this instance, "retail weight" corresponds with the Food Availability dataset that underlies LAFA, whereas the "retail weight" for meats in the LAFA dataset is on a boneless basis. The necessary conversion can be derived from the Food Availability spreadsheets, and is reported in Table 3. Changes in red meat and poultry consumption relative to the 2016 baseline are shown in Table 4. The 2028 projections provided by USDA are applied to the year 2030 in scenario 2.

Table 3. Conversions of projected red meat and poultry consumption to correspond with LAFA data

	"retail weight" from Table 17 (USDA 2019b)	Conversion factor (retail wt. to boneless)	2028 projected at LAFA retail stage (boneless)
	Lbs/capita/year		Lbs/capita/year
beef	58.4	0.956	55.8
veal	0.2	0.853	0.17
pork	54.3	0.939	51.0
lamb	1.1	0.739	0.81
Chicken (broilers + others)	95.7	0.701	67.1
turkey	15.5	0.79	12.2

Table 4. Current (2016) and projected (2028) red meat and poultry intake as estimated in USDA Agricultural Projections

	2016 at retail stage lbs (boneless) /capita/year	2028 projected at retail stage lbs (boneless) /capita/year	% change
beef	52.9	55.8	5.5%
veal	0.15	0.17	13%
pork	46.6	51.0	9.4%
lamb	0.78	0.81	3.8%
Chicken	63.1	67.1	6.3%
turkey	13.1	12.2	-6.9%

2.3.2. Scenario 3 (50% animal reduction)

In scenario 3, the intake (consumption) of animal-based foods is assumed to decrease by 50% by 2030. This includes all red meat, poultry, fish/seafood, eggs, dairy, and animal based fats. Substitutions are then made based on plant-based foods included in the Dietary Guidelines for Americans (DGA) in each of three dietary categories: protein foods, dairy foods, and added fats.

Protein foods:

Legumes (dry peas and lentils, dry beans), soy products (flour, isolate, concentrate, tofu) and nuts (tree nuts, peanuts) are listed as protein foods in the vegetarian DGA pattern. These foods were increased in the diet to substitute for decreases in animal-based protein foods. A number of options were considered in this substitution. **First**, the target for the increase of plant-based protein foods was determined based on two options, either a protein food equivalence or a caloric equivalence:

1. **Protein food quantity equivalence**
   When developing dietary recommendations and food patterns, "food pattern equivalents" are used to put foods with differing quantities of a target nutrient (in this case, protein) on an equal basis. For example, one ounce-equivalents of protein foods are defined as in Table 5:

Table 5. Definitions of one ounce equivalents of protein foods (Bowman et al. 2018)

Protein foods components	Definition of one ounce equivalent
Lean meat / poultry	28.35 grams of cooked, lean portion of meat / poultry containing no more than 2.63 grams of solid fats naturally present, per ounce equivalent
Lean seafood	28.35 grams of cooked, lean portion of seafood containing no more than 2.63 grams of fats naturally present as oils, per ounce equivalent
eggs	50 grams, raw or cooked
Nuts and seeds	½ ounce or (28.35/2) grams
Nut butters	16 grams (1 tablespoon)
Legumes	4 x the number of cup equivalents of legumes as vegetables (i.e., ¼ cup of cooked legumes as vegetables equals 1 ounce equivalent of legumes as protein foods. 1 cup equivalent of cooked legumes = 175 grams in FPED)
Soy flour, isolate or concentrate	½ ounce or (28.35/2) grams
Soy, tofu	¼ cup or (250/4) grams
Soy nuts	28.35 grams

So in this option, the plant-based protein foods were increased until the total protein food ounce-equivalents were the same as the 2016 baseline diet. Note that in the modeling, all legumes in the diet are considered protein foods and not vegetables.

2. Caloric equivalence
Plant-based foods were increased to match the calorie content of protein foods in the 2016 diet.

Second, the ratio between legumes, soy products and nuts in the 2030 diet was considered based on two options:

1. A **normative ratio** based on the vegetarian dietary patterns in DGA 2015 (legume:soy:nuts = 6:8:7 ounce-eq).
2. The **baseline ratio** seen in the 2016 LAFA diet (legume:soy:nuts = 9.3 : 1 : 8.9 ounce-eq.)

The resulting combinations of options are summarized in Table 6. In each case, option 1 is chosen to represent Scenario 3 results, whereas results involving other combinations are presented in Appendix B as evidence of the sensitivity to these modeling parameters.

Table 6. Options considered in protein foods substitution. The shaded option is presented as the Scenario 3 results whereas results based on other options are included in Appendix B.

Plant-based protein foods increased to match:	Using scale up basis:
Baseline protein food quantity (ounce-eq.)	Normative legume:soy:nuts ratio
Baseline calories from protein foods	Baseline legume:soy:nuts ratio
Baseline protein food quantity (ounce-eq.)	Normative legume:soy:nuts ratio
Baseline calories from protein foods	Baseline legume:soy:nuts ratio

The LAFA data series does not currently capture soy products in any form (confirmed through email communication with Linda Cantor, Economist, USDA ERS, August 22, 2019). To overcome this data gap challenge, the quantity of soy products consumed in the American diet was taken from the What We Eat In America NHANES 2015-2016 Food Pattern Equivalents data tables (USDA 2019a)

From these data tables, the mean consumption of soybean products (excluding calcium fortified soy milk and raw soybeans) for males and females ages 2+ = 0.10 ounce-eq. This value was used to establish a "soy products" commodity in the diet scenarios. When modeling this scenario, "soy products" are assumed to be either all soy protein isolate (used in scenario 3 and 4 results) or all tofu (presented in scenario alternatives in Appendix B). Soy protein isolate (SPI) and tofu were selected to represent the range of soy-based protein source processing, with SPI being highly processed and tofu minimally (or traditionally) processed. SPI was assumed to be the more likely substitution in the US food system, and thus used in scenarios 3 and 4. Emission factors used for SPI and tofu are given in Appendix A.

Dairy foods:

Dairy foods are composed of fluid milks, yogurt, cheeses, ice cream and other frozen dairy products, evaporated and condensed milks, and dry milks; all contribute to the dairy food pattern cup equivalents. A wide variety of plant-based milk and dairy product alternatives are presently in the marketplace. Yet, only fortified soy milk is currently recognized in the DGA as a plant-based alternative in the dairy foods category. To keep the substitution scenario tenable, fluid soy milk was added to the diet to match the total dairy cup equivalents in the baseline diet. Thus, while only fluid soymilk is included in the model, it is assumed that this represents soy-based (or other plant-based) alternatives to the variety of dairy products consumed. This simplification is also necessary because GHG emission factors are not available for the wide variety of plant-based alternatives to dairy products available. It is assumed that all substitutions of soy for dairy are fortified. Soy milk (or any other plant-based milks) also do not appear as a commodity in the LAFA data series. In this case, the necessary substitution was merely added to the diet (to a baseline amount of zero).

An alternative scenario is presented in Appendix B which substitutes 75% almond milk and 25% soy milk, which roughly approximates the current market share of alternative milks in the US (Statista 2018).

Emission factors used for soy milk and almond milk are presented in Appendix A.

Added fats:

The animal-based fats that are decreased include butter, lard, edible beef tallow, and the fat share of half and half, light and heavy cream, sour cream, cream cheese and eggnog. These reductions were

substituted by equally increasing the plant-based fats in the baseline diet (margarine, shortening, salad and cooking oils) to match the grams of added fats in the baseline diet (prior to reduction).

2.3.3. Scenario 4 (50% animal / 90% beef reduction)

Scenario 4 is modeled identically to scenario 3 except that, along with a 50% reduction of all animal-based foods, beef consumption is reduced by 90% (i.e., to 10% of the intake in the baseline diet). Plant-based protein substitutions are subsequently increased to match the baseline protein food ounce-equivalents.

2.4. Population-level impacts and cumulative emission changes

The above methods establish estimated diet-related per capita annual emissions in 2030 under the defined scenarios. We then assume a linear transition from the baseline diet to the scenario diet in 2030 (with annual time steps) and projected US populations to estimate a cumulative change in emissions from the status quo for each scenario. Population projections were taken from the US Census Bureau 2017 National Population Projections Tables (US Census Bureau 2018).

3. **Results**

3.1. Baseline diet (scenario 1)

Figure 1 and Figure 2 characterize the baseline diet by distribution of food groups by weight and calories, respectively. These represent the "average" US diet, based on a "top down" tracking of the food available for consumption in the US, and dividing it evenly across the population.
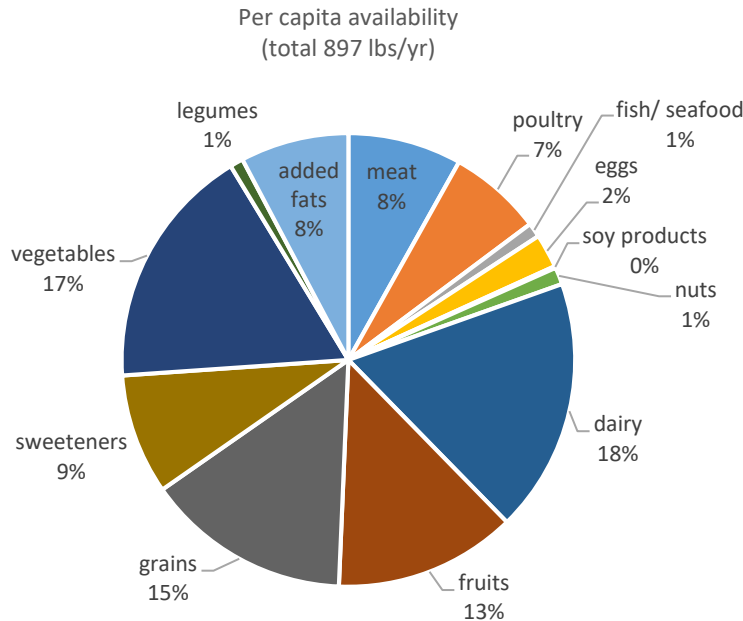
Figure 1. Distribution across food groups of the baseline diet (2016 LAFA) based on weight.
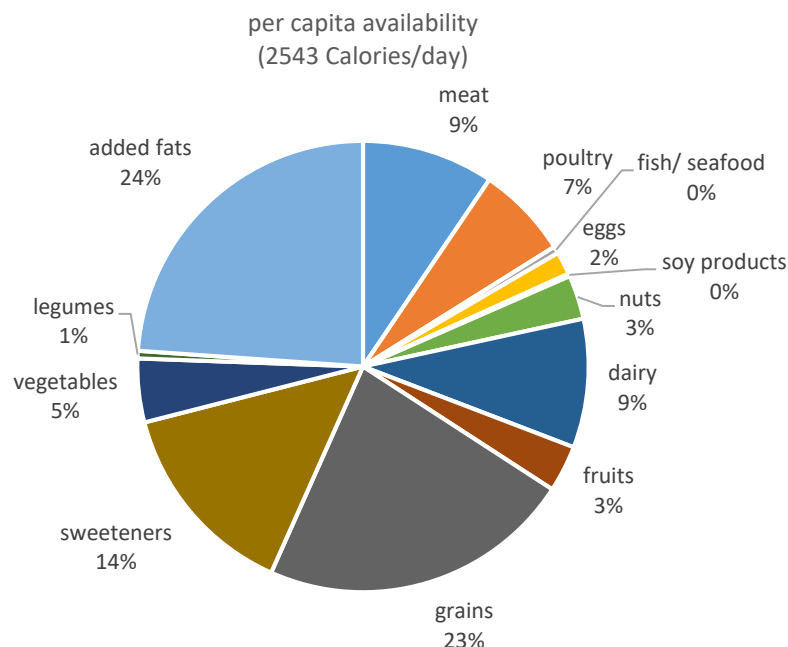
Figure 2. Distribution across food groups of the baseline diet (2016 LAFA) based on calories.

In Figure 3, the distribution of GHGE across the same food groups demonstrates the dominance of red meat, and especially beef, in the average US diet's carbon footprint. The total emissions associated with producing the average US diet amounts to 5.0 kg CO_2 eq. per person per day. As shown in Table 7 this value agrees well with a number of previous estimates based on both similar and differing methodological approaches.

Table 7. Comparisons of GHGE estimates associated with producing the average US diet.

US diet average emissions (kg CO_2 eq/cap/day)	Methodological approach	reference
5.0	2016 LAFA diet, dataFIELD emission factors	This study
5.0	2010 LAFA diet, different collection of emission factors	(Heller and Keoleian 2015)
4.7	2005-2010 NHANES diets, dataFIELD emission factors	(Heller et al. 2018)
4.7*	2007-2008 NHANES, environmental input-output model based approach to emissions	(Hitaj et al. 2019)

*This study considers emissions through retail. The value presented here represents only the "farm and agribusiness" stage, to be consistent with boundary conditions of other studies.

GHGE distribution
total = 5.0 kg CO_2 eq/capita/day
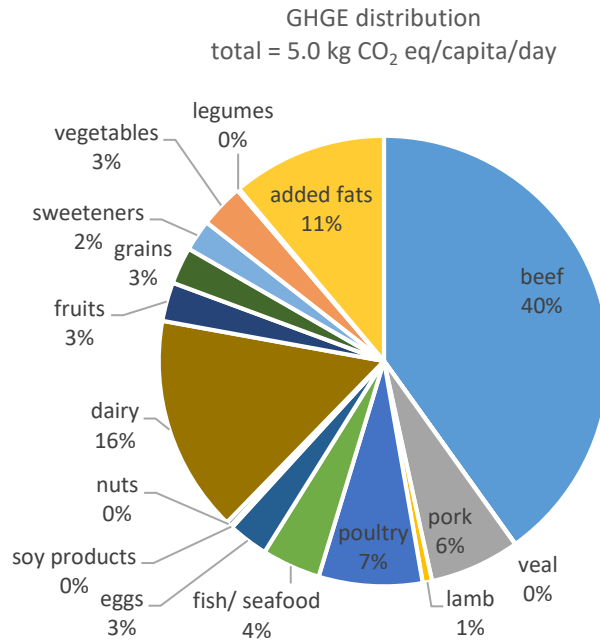
Figure 3. Distribution of GHGE across food groups of the baseline diet (2016 LAFA).

The emission estimates presented in Figure 3 and Table 7 include contributions from food losses, as agricultural production of food loss and waste carries the same environmental burden as consumed food. Edible losses contribute 29% to the total diet GHGE presented here, and losses of animal-based foods represent 80% of that. In other words, edible losses of animal-based foods contribute 23% to the total diet GHGE. Disaggregating the meat, poultry and dairy groups in the baseline diet as in Table 7 allows for a better understanding of current consumption patterns and contributions to dietary GHGE. All animal-based foods (including animal-based added fats) together contribute 82% of the total diet GHGE.

Table 8. Availability of meat, poultry, and dairy in the baseline diet and contributions to dietary GHGE

		Per capita availability (adjusted for loss)			kg CO_2 eq /capita/day	% of total diet GHGE
		Lbs/year	Oz/day	grams/day		
meat	beef	40.5	1.78	50.32	2.00	40.1%
	veal	0.1	0.00	0.11	0.00	0.0%
	pork	31.6	1.39	39.32	0.32	6.5%
	lamb	0.5	0.02	0.68	0.03	0.7%
poultry	chicken	51.5	2.26	64.05	0.33	6.6%
	turkey	8.2	0.36	10.23	0.04	0.8%
dairy	fluid milks	105.0	4.60	130.43	0.25	5.1%
	yogurt	9.6	0.42	11.88	0.02	0.5%
	cheeses	25.1	1.10	31.20	0.36	7.2%
	ice cream, frozen dairy	15.1	0.66	18.79	0.07	1.4%
	evap. & condensed milks	5.6	0.24	6.92	0.03	0.6%
	dry milks	2.1	0.09	2.59	0.04	0.9%

3.2. Scenario 2 (USDA meat projections)

The changes in meat consumption projected by the USDA reported in Table 4 lead to a slight increase in the calories (2563 Cal/capita/day) and the diet carbon footprint in 2030. The average diet GHGE increases to 1875 kg CO_2 eq. per capita per year (5.14 kg CO_2 eq. per capita per day) and the contribution from meat increases to 49%, with 41% coming from beef. Contributions by food type are presented along with other scenarios in Table 9.

3.3. Scenario 3 (50% animal reduction)

Scenario 3 involves a 50% reduction in the weight availability of all animal-based foods in the diet, increasing the amount of legumes, soy products and nuts to match the baseline diet ounce equivalents of protein foods, adding soy milk to match the baseline diet cup equivalents of dairy, and increasing plant based fats to make up for reduced animal-based fats.

The resulting diet can be seen in Table 9, in comparison to the baseline. In this scenario, the quantity of nuts in the diet increases by a factor of 1.9, soy products by a factor of 21, and legumes by a factor of 1.6. Total calories are slightly lower but still within 2% of the baseline diet. Diet related GHGE in this scenario decrease by 35% from the baseline to 3.3 kg CO_2 eq/capita/day. The distribution of GHGE by food group is shown in the pie chart in Figure 4. After a 50% reduction in animal-based foods, meat still contributes 36% to the diet's carbon footprint, with beef representing most of this at 31% of the total. Edible food losses remain at 29% of the total diet GHGE.
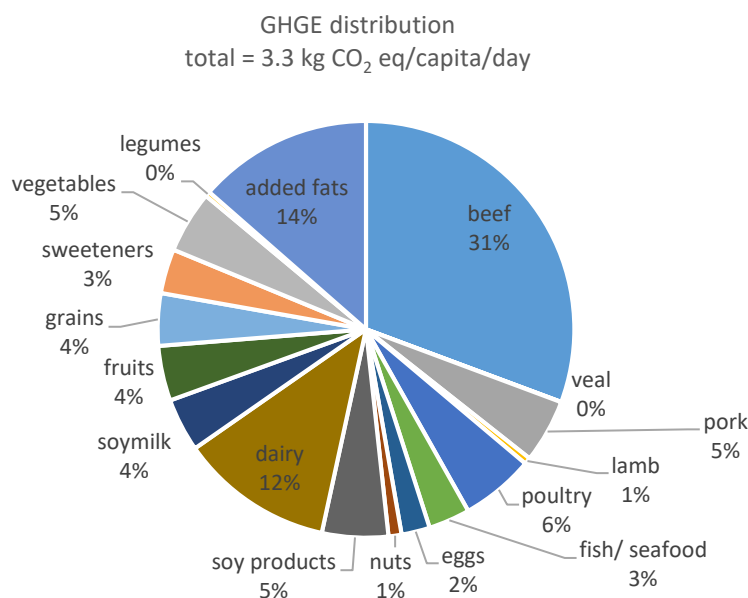
Figure 4. Distribution of GHGE by food group for Scenario 3

Results from the other substitution options explored in this study are presented in Appendix B. Each of these options differs by less than 4% in total diet GHGE from our main scenario 3 result.

3.4. Scenario 4 (50% animal / 90% beef reduction)

Scenario 4 extends scenario 3 by increasing the reduction in beef to 90% (food quantity, calories and GHGE also shown in Table 9). Under this scenario, the quantity of nuts in the diet increases by a factor of 2.2, soy products by a factor of 24, and legumes by a factor of 1.8. Per capita beef consumption decreases to 4.0 lbs per year, or 0.18 oz. per day. At 2.4 kg CO_2 eq per capita per day, diet GHGE decrease to 51% of the baseline diet, and meat now represent only 16% of the total with beef representing half of that.

3.5. Cumulative emission changes

Table 10 shows the results of extending average per capita diet emissions to the population level for the projection scenarios considered in this study. Here, a linear transition is assumed from the baseline diet in 2016 to the projected scenario diet in 2030. Using this assumption and population projections from the US Census Bureau, we estimate annual national emissions from the production of the projected US diet, as well as the potential changes in emissions realized in switching from the status quo (baseline diet maintained unchanged to 2030) to each of the other scenarios. These changes in annual diet-related emissions are also shown graphically in Figure 5. Relative to the status quo, scenario 3 – replacing 50% of all animal-based foods with plant-based alternatives – leads to an emission reduction of 224 million metric tonnes of CO_2eq. (MMT) in 2030, a reduction equivalent to the annual emissions of 47.5 million of today's average passenger vehicles (US EPA 2019a). This target of 50% substitution by 2030 results in an estimated cumulative reduction of 1634 MMT between 2016 and 2030. By further replacing 90% of beef, the cumulative emission reduction increases to 2408 MMT.

Table 9. Comparisons by food type of food and caloric availability and GHGE between all diet scenarios.

	Per capita availability (lbs/year)				Available daily Calories (Cal/capita/day)				GHGE (kg CO₂eq /capita/year)			
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4
TOTAL	898.1	904.9	912.9	904.4	2543	2563	2487	2465	1819.4	1874.5	1189.1	890.5
beef	40.5	42.7	20.2	4.0	146	154	73	15	729.4	769.3	364.7	72.9
veal	0.1	0.1	0.0	0.0	0	0	0	0	0.4	0.5	0.2	0.2
pork	31.6	34.6	15.8	15.8	93	102	46	46	117.6	128.8	58.8	58.8
lamb	0.5	0.6	0.3	0.3	2	2	1	1	12.2	12.8	6.1	6.1
poultry	59.8	62.4	29.9	29.9	169	177	84	84	135.4	141.8	67.7	67.7
fish/ seafood	9.2	9.2	4.6	4.6	13	13	6	6	76.6	76.6	38.3	38.3
eggs	21.6	21.6	10.8	10.8	42	42	21	21	52.4	52.4	26.2	26.2
nuts	11.0	11.0	21.0	23.7	80	80	152	172	6.4	6.4	12.0	13.6
soy products	1.1	1.1	23.0	26.1	4.8	4.8	97	110	3.0	3.0	61.1	69.3
dairy	162.5	162.5	81.2	81.2	235	235	117	117	283.3	283.3	141.6	141.6
soymilk	*	*	148.9	148.9	*	*	99	99	*	*	49.2	49.2
fruits	116.6	116.6	116.5	116.5	85	85	85	85	50.8	50.8	50.8	50.8
grains	132.5	132.5	131.3	131.3	572	572	594	594	48.3	48.3	48.3	48.3
sweeteners	77.1	77.1	77.1	77.1	365	365	365	365	41.0	41.0	41.0	41.0
vegetables	156.1	156.1	156.1	156.1	116	116	116	116	57.3	57.3	57.3	57.3
legumes	8.5	8.5	13.8	15.6	14	14	22	25	2.8	2.8	4.6	5.2
added fats	69.4	69.4	62.4	62.4	607			607	608	202.5	202.5	161.1	144.0

*soy milk is not captured in the LAFA dataset and therefore does not appear in the baseline diet.

Scenario 1 = baseline, or status quo, diet
Scenario 2 = USDA meat projections
Scenario 3 = 50% animal reduction
Scenario 4 = 50% animal / 90% beef reduction

Table 10. Population level emissions and changes from the status quo for each scenario. MMT = million metric tonnes CO_2 eq.

Year	Population	Scenario 1 (status quo)		scenario 2			scenario 3			scenario 4		
	in thousands	kg CO_2 eq /cap/yr	MMT/yr	kg CO_2 eq /cap/yr	MMT/yr	annual change from status quo	kg CO_2 eq /cap/yr	MMT/yr	annual change from status quo	kg CO_2 eq /cap/yr	MMT/yr	annual change from status quo
2016	323,128	1819.4	587.9	1819.4	587.9	0.0	1819.4	587.9	0.0	1819.4	587.9	0.0
2017	325,511	1819.4	592.2	1823.4	593.5	1.3	1774.4	577.6	-14.7	1753.1	570.6	-21.6
2018	327,892	1819.4	596.6	1827.3	599.2	2.6	1729.4	567.1	-29.5	1686.7	553.1	-43.5
2019	330,269	1819.4	600.9	1831.2	604.8	3.9	1684.4	556.3	-44.6	1620.4	535.2	-65.7
2020	332,639	1819.4	605.2	1835.2	610.5	5.2	1639.3	545.3	-59.9	1554.0	516.9	-88.3
2021	334,998	1819.4	609.5	1839.1	616.1	6.6	1594.3	534.1	-75.4	1487.7	498.4	-111.1
2022	337,342	1819.4	613.8	1843.0	621.7	8.0	1549.3	522.6	-91.1	1421.3	479.5	-134.3
2023	339,665	1819.4	618.0	1847.0	627.4	9.4	1504.2	510.9	-107.1	1355.0	460.2	-157.8
2024	341,963	1819.4	622.2	1850.9	632.9	10.8	1459.2	499.0	-123.2	1288.6	440.7	-181.5
2025	344,234	1819.4	626.3	1854.9	638.5	12.2	1414.2	486.8	-139.5	1222.3	420.7	-205.6
2026	346,481	1819.4	630.4	1858.8	644.0	13.6	1369.2	474.4	-156.0	1155.9	400.5	-229.9
2027	348,695	1819.4	634.4	1862.7	649.5	15.1	1324.1	461.7	-172.7	1089.6	379.9	-254.5
2028	350,872	1819.4	638.4	1866.7	655.0	16.6	1279.1	448.8	-189.6	1023.2	359.0	-279.4
2029	353,008	1819.4	642.3	1870.6	660.3	18.1	1234.1	435.6	-206.6	956.9	337.8	-304.5
2030	355,101	1819.4	646.1	1874.5	665.7	19.6	1189.1	422.2	-223.8	890.5	316.2	-329.9
cumulative change from status quo, MMT (2016-2030)						142.8			-1633.8			-2407.5
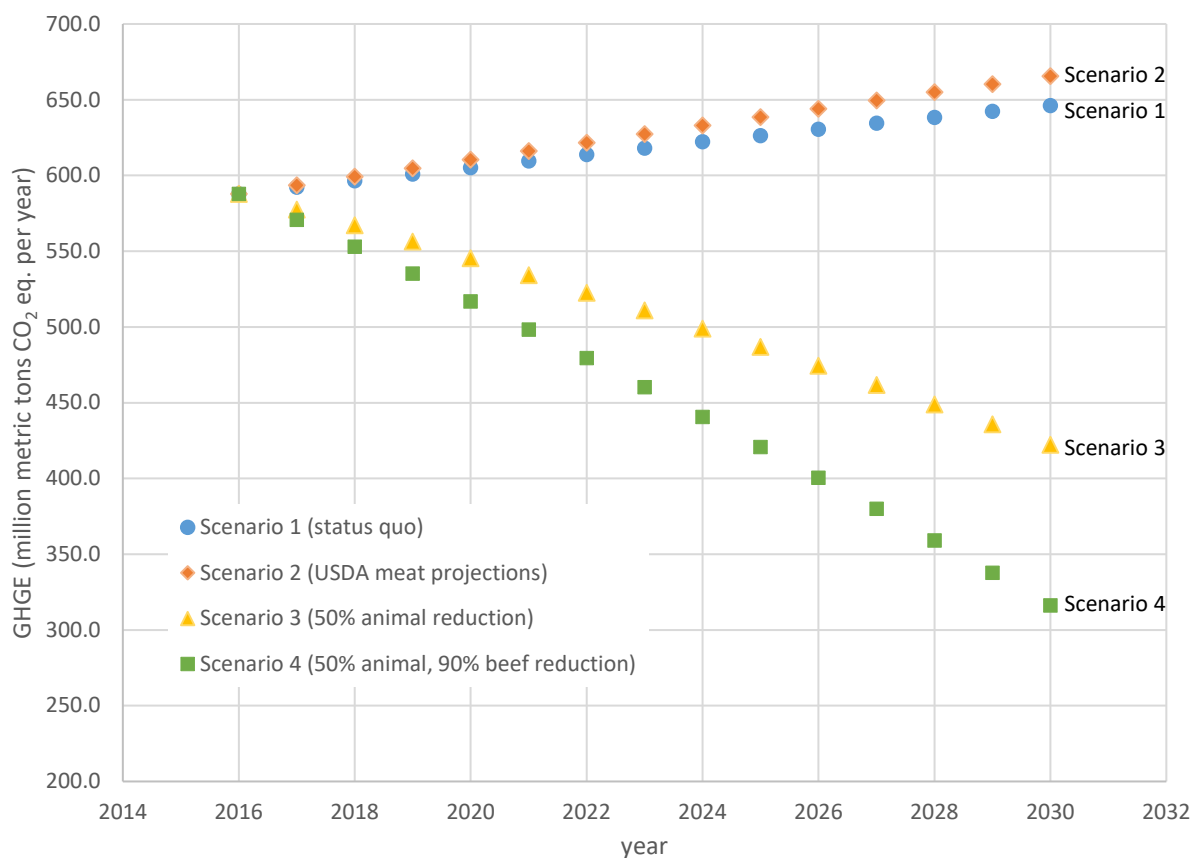
Figure 5. Visual representation of the change in population-level emissions associated with projected US diet scenarios (data from Table 10).

4. Discussion

The scenarios presented in this report are intended to offer first-order estimations of the potential changes in greenhouse gas emissions associated with a US population-wide shift in dietary patterns. Replacing 50% of animal-based foods with plant-based alternatives (scenario 3) reduces the per capita emissions from the diet by 35% of the status quo baseline. Further reducing beef by 90% of current levels while replacing 50% of other animal-based foods (scenario 4) results in a per capita decrease in GHGE of 51%. These changes are in line with potential emission reductions reported elsewhere for a wide range of contexts (see, e.g., the review by Aleksandrowicz et al. (2016)). Results presented in Appendix B suggest that these emission reductions demonstrate minimal sensitivity (less than +/- 4% change) to substitution model parameter assumptions.

Consideration of the population-level emissions associated with dietary patterns helps demonstrate the potential scope of emission reductions associated with shifts in dietary patterns. In the absence of dietary change, emissions associated with producing the food that we eat are expected to increase 9% by 2030 due to population growth. Scenario 3 – replacing 50% of all animal-based foods with plant-based alternatives – leads to an emission reduction of 224 million metric tonnes of CO_2eq. (MMT) in

2030. This diet-related reduction of 224 MMT would represent 24% of the reductions from the total US emissions in 2017 that are necessary to meet the US Intended Nationally Determined Contribution to the United Nations Framework Convention on Climate Change[1]. Assuming a linear transition from the baseline diet in 2016 to the scenario 3 diet in 2030 results in a total cumulative reduction in emissions of 1634 MMT over 15 years. Clearly, a more accelerated transition will be needed to meet these projections, as we are already 3 years behind the timeline.

Food systems are extremely complex due to the diversity of food types, production methods and locations, and dietary patterns, and a number of assumptions are necessary to evaluate the presented scenarios. We did not investigate other dietary changes that might accompany the substitution of animal-based foods for plant-based foods (e.g., changes in grain consumption, fruits, vegetables, or added fats). Further, secondary effects on production, market supply, and prices, either within the US or internationally, were not considered. In other words, it is assumed that agricultural production in the US adjusts to changes in domestic demand (reduced demands for animal-based foods, increased demands for plant-based alternatives) without significant increases in exports to other countries. Inclusion of such secondary effects, for example through global agro-economic models, in addition to requiring efforts beyond the scope of this study, has been shown to be highly uncertain and dependent on the tools and models applied (Stehfest et al. 2013). In addition, we have not considered indirect economic rebound effects: as the projected scenarios may results in reduced per capita spending on food, these savings could potentially be spent on other purchases/activities with greater environmental impact.

Estimates of greenhouse gas emissions are based on generic commodity-specific emission factors. While considered to be representative and the best data available, these emission factors are not specific to US production conditions. There is a broad need for further research and consistent data development on the environmental implications of US agricultural production systems (Heller et al. 2013). In addition, it was assumed here that average emission factors remain static across changes in dietary patterns. This assumption is particularly interesting to examine at low beef production levels. In the baseline scenario, it is assumed that roughly 20% of the beef consumed in the US is derived from dairy herds. The emissions associated with beef from dairy are typically lower than from dedicated beef cattle because the resources and emissions associated with maintaining the breeding herd are shared between two products – milk and meat (Tichenor 2015; Tichenor et al. 2017; Rotz et al. 2019). Under scenario 3 where all animal-based foods are reduced, it is reasonable to assume that the percentage of beef from dairy would remain roughly unchanged. With additional beef reduction in scenario 4, however, a larger percentage of the US beef market could potentially originate from dairy herds, since dairy is not reduced further in this scenario, and calves originating from dairy herds and cull dairy cows would likely be lower cost beef production options. Further, under these reduced production scenarios, byproducts from food processing and ethanol production (distiller's grains) will likely become a larger fraction of the feed used in beef production. Eshel et al. (2018) estimate that current availability of these byproduct feeds could support around 10% of today's beef consumption levels. While it is extremely difficult to predict beef

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[1] The US Intended Nationally Determined Contribution to the United Nations Framework Convention on Climate Change states that "the United States intends to achieve an economy-wide target of reducing its greenhouse gas emissions by 26-28 per cent below its 2005 level in 2025." (UNFCCC) US EPA reports 2005 net emissions at 6599 MMT (US EPA 2019b), making a 27% reduction from this baseline equal to an annual net emissions below 4817 MMT. The latest US EPA inventory of US Greenhouse Gas Emissions and Sinks indicates that the net emissions in 2017 were 5743 MMT (US EPA 2019b)

industry practices under such projection scenarios, the changes described here (i.e. a larger fraction of cattle from dairy herds or changing feeds) that may result from large decreases in beef production would likely lead to lower emissions per unit of production for beef (lower emission factors), thus resulting in even greater emission reductions than reported here.

The GHGE estimates presented here capture only agricultural production and basic processing of processed commodity foods (flours, oils, sugars, dairy products, juices, dried fruits and vegetables). The downstream stages of additional processing, packaging, distribution, retail, food service and home storage and cooking are not included. This is necessary in diet-level studies because a) information on the environmental impact of these downstream stages is limited and b) defining and characterizing diet at the commodity level precludes differentiation of processed food products that are combinations of these commodity foods. Results from a recent study that utilizes environmentally extended input-output methods to link environmental impact to economic interactions between industrial sectors, suggests that a plant-based diet would not increase after-farm emissions (Hitaj et al. 2019).

While this study has focused on greenhouse gas emissions, food production and dietary choices play a notable role in other environmental impacts, including water use, water pollution (eutrophication), land use, and biodiversity. Existing studies suggest that reductions in animal-based foods in the diet can also contribute to decreased impacts in these categories as well (Aleksandrowicz et al. 2016; Springmann et al. 2018a; Springmann et al. 2018b; Willett et al. 2019). In addition, epidemiological studies provide evidence that reductions in animal-based foods can lead to reductions in a number of non-communicable disease risks, suggesting that the projected diet scenarios with reduced GHGE could also lead to improved health outcomes (Springmann et al. 2018b; Clark et al. 2019; Willett et al. 2019).

5. Conclusions

Recent IPCC reports demonstrate that unprecedented reductions in greenhouse gas emissions are required by 2030 in order to keep warming to 1.5 degrees, a level now seen as necessary to avoid climate instability and irreversible tipping points (IPCC 2018). Responses to this urgent call to action can no longer afford to debate where reductions should occur but must come from all sectors of society and our economy. In this study, we model the dramatic reductions in greenhouse gas emissions that are possible through significant changes in diet in the US. Reducing the intake of all animal-based foods by 50% in the US diet has the potential to reduce diet-related greenhouse gas emissions by 35%. Achieving such a goal by 2030 would result in an expected emission reduction of 224 MMT per year from the current diet, bringing the US 24% closer (based on 2017 total emissions) to meeting its Nationally Determined Contribution. Further reducing beef consumption by 90% of current levels, combined with 50% reductions in other animal-based foods, has the potential to bring down emissions in 2030 by 330 MMT below the current diet, or 36% closer to the US Nationally Determined Contribution.

This study demonstrates that sizable reductions in greenhouse gas emissions are possible through reductions in animal-based foods in the average US diet. These results further emphasize the importance of addressing agriculture, food systems and nutritional education when considering climate change interventions. Such dietary changes will require the concerted efforts of policymakers, the food industry and consumers. The projection scenarios presented here point to the urgency of such efforts, as decisions made now will have a cumulative impact over the next decade.

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Appendix A

Appendix A: Emission Factors used for LAFA food commodities

The table below details the GHGE emission factors assigned to each LAFA food commodity. Unless otherwise noted, linkages were made to average emission factors designated in the dataFIELD database, available at: http://css.umich.edu/page/datafield. dataFIELD is an aggregation of results from the life cycle assessment literature (LCA) on the production of foods. Note that references to an "entry" indicate a unique result from a given LCA study recorded in dataFIELD. Emission factors are in all cases based on Intergovernmental Panel on Climate Change (IPCC) 100-year time horizon global warming potentials (GWP) (i.e., CO_2 equivalents for non-CO_2 greenhouse gases). GWPs have evolved slightly in each successive IPCC report as the scientific understanding of climate change has developed, and given the temporal range of the underlying LCA literature (2005-2016), the specific GWPs employed differ. Further, as many studies do not report emission inventories, it was not possible to normalize emission factors using consistent GWPs. While this introduces some methodological uncertainty, it is considered negligible relative to the uncertainties introduced by agricultural growing practices, seasonal variability, etc.

Note that throughout, meats (including poultry and fish) are on a boneless, edible basis. The weight bases of other foods have been adjusted to best match the basis used in LAFA.

LAFA designation		Emission factor assignment from dataFIELD		
Food group	Food commodity	Direct link in dataFIELD?	FCID description (dataFIELD) or notes on proxy	GHGE (CO₂ eq /kg)
meat	beef		Accounts for beef from dairy[1]	30.4
meat	veal	Y	1 entry	5.9
meat	pork	Y	Pork, meat	5.6
meat	lamb	Y	Sheep, meat	34.7
poultry	chicken	Y	Chicken, meat	4.2
poultry	turkey	Y	Turkey, meat	2.6
fish/ seafood	fresh and frozen fish		average of all finfish entries	4.1
fish/ seafood	fresh and frozen shellfish		average of all shellfish entries	23.4
fish/ seafood	canned salmon		average of salmon entries	2.5
fish/ seafood	canned sardines	Y	one sardine entry	1.4
fish/ seafood	canned tuna	Y	Fish-saltwater finfish, tuna	2.1
fish/ seafood	canned shellfish		average of all shellfish entries	23.4
fish/ seafood	other canned fish		average of all finfish entries	4.1
fish/ seafood	cured fish		average of all finfish entries	4.1
eggs	eggs	Y	eggs	3.3
soy products	soybean products		See footnote [2]	4.9
nuts	peanuts	Y	Peanut	0.4
nuts	almonds	Y	Almond	2.3
nuts	hazelnuts	Y	Hazelnut	1.0
nuts	pecans	Y	Pecan	2.1
nuts	walnuts	Y	Walnut	1.7
nuts	macadamia	Y	Macadamia nut	2.1
nuts	pistachios	Y	Pistachio	1.8
nuts	other tree nuts		using average of all nuts	2.1
nuts	coconut	Y	Coconut, dried	1.4
dairy	plain whole milk		milk	1.3
dairy	2% milk		milk	1.3
dairy	1% milk		milk	1.3
dairy	skim milk		milk	1.3
dairy	whole flavored milk		milk	1.3

dairy	lowfat flavored milk		milk	1.3
dairy	buttermilk		milk	1.3
dairy	yogurt		average of 3 yogurt entries, at processor gate	1.3
dairy	cheddar cheese		average of 7 cheese entries, at processor gate	8.6
dairy	other American Cheese		average of 7 cheese entries, at processor gate	8.6
dairy	Mozarella cheese		average of 7 cheese entries, at processor gate	8.6
dairy	Other Italian cheese		average of 7 cheese entries, at processor gate	8.6
dairy	Swiss cheese		average of 7 cheese entries, at processor gate	8.6
dairy	Brick cheese		average of 7 cheese entries, at processor gate	8.6
dairy	Muenster cheese		average of 7 cheese entries, at processor gate	8.6
dairy	Blue cheese		average of 7 cheese entries, at processor gate	8.6
dairy	other miscellaneous cheese		average of 7 cheese entries, at processor gate	8.6
dairy	regular cottage cheese		1 entry[3]	1.8
dairy	lowfat cottage cheese		1 entry[3]	1.8
dairy	ice cream		avg of 4 entries from (Konstantas et al. 2019), raw materials and manufacturing only	2.4
dairy	ice milk		avg of 4 entries from (Konstantas et al. 2019), raw materials and manufacturing only	2.4
dairy	Frozen yogurt and other miscellaneous frozen product		avg of 4 entries from (Konstantas et al. 2019), raw materials and manufacturing only	2.4
dairy	Evaporated and condensed canned whole milk		1 entry from Canada (2013 Verge et al)	3.1
dairy	Evaporated and condensed bulk whole milk		1 entry[3]	3.1
dairy	Evaporated and condensed bulk and canned skim mil		1 entry [3]	3.1
dairy	dry whole milk		1 entry[3]	10.1
dairy	nonfat dry milk		1 entry[3]	10.1
dairy	dry buttermilk		1 entry[3]	10.1
dairy	dairy share of eggnog		cream as proxy	3.1
soymilk	soymilk		See footnote [4]	0.5
	almond milk		See footnote [5]	0.3
Fruits	fresh oranges	Y	Orange	0.2
Fruits	fresh tangerines and tangelos	Y	Tangerine	0.3
Fruits	fresh grapefruit	Y	Grapefruit	0.6
Fruits	fresh lemons	Y	Lemon	0.2
Fruits	fresh limes	Y	Lime	0.5
Fruits	fresh apples	Y	Apple, fruit with peel	0.2
Fruits	fresh apricots	Y	Apricot	0.4
Fruits	fresh avocados	Y	Avocado	0.4
Fruits	fresh bananas	Y	Banana	0.2
Fruits	fresh blueberries	Y	Blueberry	0.5
Fruits	fresh cantaloupe	Y	Cantaloupe	0.3
Fruits	fresh cherries	Y	Cherry	0.5
Fruits	fresh cranberries	Y	Cranberry	1.4
Fruits	fresh grapes	Y	Grape	0.5
Fruits	fresh honeydew melons	Y	Honeydew melon	0.1
Fruits	fresh kiwifruit	Y	Kiwifruit, fuzzy	0.2
Fruits	fresh mangoes	Y	Mango	0.4
Fruits	fresh papaya	Y	Papaya	0.1
Fruits	fresh peaches	Y	Peach	0.3
Fruits	fresh pears	Y	Pear	0.2
Fruits	fresh pineapple	Y	Pineapple	0.5
Fruits	fresh plums	Y	Plum	0.5

Fruits	fresh raspberries	Y	Raspberry	0.2
Fruits	fresh strawberries	Y	Strawberry	0.6
Fruits	fresh watermelon	Y	Watermelon	1.0
Fruits	canned apples and applesauce		Apple, fruit with peel	0.2
Fruits	canned apricots		Apricot	0.4
Fruits	canned sweet cherries		Cherry	0.5
Fruits	canned tart cherries		Cherry	0.5
Fruits	canned peaches		Peach	0.3
Fruits	canned pears		Pear	0.2
Fruits	canned pineapple		Pineapple	0.5
Fruits	canned plums		Plum	0.5
Fruits	canned olives		Olive	0.4
Fruits	frozen blackberries		Blackberry	0.6
Fruits	frozen blueberries		Blueberry	0.5
Fruits	frozen raspberries		Raspberry	0.2
Fruits	frozen strawberries		Strawberry	0.6
Fruits	frozen other berries		berry average	0.6
Fruits	frozen apples		Apple, fruit with peel	0.2
Fruits	frozen apricots		Apricot	0.4
Fruits	frozen sweet cherries		Cherry	0.5
Fruits	frozen tart cherries		Cherry	0.5
Fruits	frozen peaches		Peach	0.3
Fruits	frozen plums and prunes		Plum	0.5
Fruits	dried apples	Y	Apple, dried	1.3
Fruits	dried apricots	Y	Apricot, dried	1.4
Fruits	dried dates	Y	Date	1.8
Fruits	dried figs	Y	Fig, dried	1.8
Fruits	dried peaches	Y	Peach, dried	1.7
Fruits	dried pears	Y	Pear, dried	1.1
Fruits	dried plums (prunes)	Y	Plum, prune, dried	1.5
Fruits	raisins	Y	Grape, raisin	0.7
Fruits	grapefruit juice	Y	Grapefruit, juice	1.6
Fruits	lemon juice	Y	Lemon, juice	0.3
Fruits	lime juice	Y	Lime, juice	1.9
Fruits	orange, tangerine and tangelo juice		Orange, juice	0.5
Fruits	apple juice	Y	Apple, juice	1.3
Fruits	cranberry juice	Y	Cranberry, juice	1.7
Fruits	grape juice	Y	Grape, juice	1.6
Fruits	pineapple juice	Y	Pineapple, juice	1.9
Fruits	prune juice	Y	Plum, prune, juice	1.4
Grains	wheat flour	Y	Wheat, flour	0.4
Grains	rye flour	Y	Rye, flour	0.4
Grains	rice		avg of brown and white rice FCID listings	1.8
Grains	corn flour and meal	Y	Corn, field, flour	0.6
Grains	corn hominy and grits		Corn, field, meal	0.6
Grains	corn starch	Y	Corn, field, starch	0.8
Grains	oat products	Y	Oat, groats/rolled oats	0.5
Grains	barley products	Y	Barley, pearled barley	0.4
sweeteners	refined cane and beet sugar		avg of sugarcane and beet sugar FCID entries	0.5
sweeteners	edible syrups		Maple syrup	6.8
sweeteners	honey	Y	Honey	2.4
sweeteners	high fructose corn syrup	Y	Corn, field, syrup	0.8
sweeteners	glucose		Corn, field, syrup	0.8

sweeteners	dextrose		Corn, field, syrup	0.8
vegetables	fresh artichokes	Y	Artichoke, globe	0.3
vegetables	fresh asparagus	Y	Asparagus	1.1
vegetables	fresh bell peppers	Y	Pepper, bell	0.4
vegetables	fresh broccoli	Y	Broccoli	0.5
vegetables	fresh Brussels sprouts	Y	Brussels sprouts	0.4
vegetables	fresh cabbage	Y	Cabbage	0.2
vegetables	fresh carrots	Y	Carrot	0.1
vegetables	fresh cauliflower	Y	Cauliflower	0.4
vegetables	fresh celery	Y	Celery	0.3
vegetables	fresh collard greens	Y	Collards	0.1
vegetables	fresh sweet corn	Y	Corn, sweet	0.3
vegetables	fresh cucumbers	Y	Cucumber	0.4
vegetables	fresh eggplant	Y	Eggplant	0.4
vegetables	fresh escarole/endive	Y	Endive	0.1
vegetables	fresh garlic	Y	Garlic, bulb	0.6
vegetables	fresh kale	Y	Kale	0.1
vegetables	fresh head lettuce	Y	Lettuce, head	0.2
vegetables	fresh romaine and leaf lettuce	Y	Lettuce, leaf	0.2
vegetables	fresh lima beans	Y	Bean, lima, succulent	0.7
vegetables	fresh mushrooms	Y	Mushroom	3.0
vegetables	fresh mustard greens	Y	Mustard greens	0.1
vegetables	fresh okra	Y	Okra	0.4
vegetables	fresh onions	Y	Onion, bulb	0.2
vegetables	fresh potatoes	Y	Potato, tuber, w/peel	0.2
vegetables	fresh pumpkin	Y	Pumpkin	0.2
vegetables	fresh radishes	Y	Radish, roots	0.2
vegetables	fresh snap beans	Y	Bean, snap, succulent	0.7
vegetables	fresh spinach	Y	Spinach	0.2
vegetables	fresh squash	Y	Squash, winter	0.0
vegetables	fresh sweet potatoes	Y	Sweet potato	0.2
vegetables	fresh tomatoes	Y	Tomato	0.4
vegetables	fresh turnip greens	Y	Turnip, greens	0.1
vegetables	canned asparagus		Asparagus	1.1
vegetables	canned snap beans		Bean, snap, succulent	0.7
vegetables	canned cabbage (sauerkraut)		Cabbage	0.2
vegetables	canned carrots		Carrot	0.1
vegetables	canned sweet corn		Corn, sweet	0.3
vegetables	canned cucumbers (pickles)		Cucumber	0.4
vegetables	canned green peas		Pea, succulent	1.3
vegetables	canned mushrooms		Mushroom	3.0
vegetables	canned chile peppers		Pepper, nonbell	0.7
vegetables	canned potatoes		Potato, tuber, w/peel	0.2
vegetables	canned tomatoes		Tomato	0.4
vegetables	other canned vegetables		mean, vegetables	0.6
vegetables	frozen asparagus		Asparagus	1.1
vegetables	frozen snap beans		Bean, snap, succulent	0.7
vegetables	frozen broccoli		Broccoli	0.5
vegetables	frozen carrots		Carrot	0.1
vegetables	frozen cauliflower		Cauliflower	0.4
vegetables	frozen sweet corn		Corn, sweet	0.3
vegetables	frozen green peas		Pea, succulent	1.3
vegetables	frozen green lima beans		Bean, lima, succulent	0.7
vegetables	frozen potatoes		Potato, tuber, w/peel	0.2

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vegetables	frozen spinach		Spinach	0.2
vegetables	misc. frozen vegetables		mean, vegetables	0.6
vegetables	dehydrated onions	Y	Onion, bulb, dried	2.1
vegetables	dehydrated potatoes	Y	Potato, dry (granules/ flakes)	1.3
vegetables	potato chips	Y	Potato, chips	1.5
legumes	dry peas and lentils		avg of lentil seed & dry pea	1.3
legumes	dry black beans	Y	Bean, black, seed	0.3
legumes	dry great northern beans	Y	Bean, great northern, seed	0.3
legumes	dry lima beans	Y	Bean, lima, seed	0.3
legumes	dry navy beans	Y	Bean, navy, seed	0.3
legumes	dry pinto beans	Y	Bean, pinto, seed	0.3
legumes	dry red kidney beans	Y	Bean, kidney, seed	0.3
legumes	other dry beans	Y	Bean, kidney, seed	0.3
added fats	butter		avg of 4 entries	8.3
added fats	margarine		avg of 3 entries, total LC	1.4
added fats	lard		Pork, meat	5.6
added fats	edible beef tallow		beef	30.4
added fats	shortening		margarine as proxy	1.4
added fats	salad and cooking oils		avg all oils	3.6
added fats	other edible fats and oils		avg all oils	3.6
added fats	fat share of half and half		Cream as proxy	3.1
added fats	light cream		2 entries	3.1
added fats	heavy cream		3 entries	3.1
added fats	sour cream		1 entry[3]	2.5
added fats	cream cheese		Cream as proxy	3.1
added fats	fat share of eggnog		Cream as proxy	3.1

[1] The value reported here accounts for 19.5% of total beef production originating from dairy herds, which typically represents a lower carbon footprint. Beef values from dataFIELD are as follows: beef from beef cattle: 33.1 kg CO_2eq/kg boneless (average of 95 entries); beef from dairy: 19.0 kg CO_2eq/kg boneless (average of 10 entries).

[2] Tofu: average of 2 values: 2.2 kg CO_2eq/kg, from (Poore and Nemecek 2018), (after removing distribution, packaging, retail, losses); 1.6 kg CO_2eq/kg from (Blonk et al. 2008) = 1.9 kg CO_2eq/kg

[2] Soy protein isolate: 4.94 kg CO_2eq/kg from (Munoz and Thrane 2015) (representative of US production, converted from /kg protein to /kg using 0.81 kg protein/kg).

[3] Canadian study: (Vergé et al. 2013)

[4] soymilk: average of 3 values, from: (Poore and Nemecek 2018), (after removing distribution, packaging, retail, losses); (Clune et al. 2017); (Grant and Hicks 2018)

[5] almond milk: average of 3 values, from: (Clune et al. 2017); (Grant and Hicks 2018); (Ho et al. 2016)

Appendix B: Results from Scenario modeling alternatives

A number of modeling choices were made in building the plant-based substitution scenarios in this study. Here, we explore the influence of alternative choices for these modeling parameters.

Table B-1 provides an abbreviated summary of these alternatives, along with their associated diet-level emissions. In Scenario 3, plant-based protein foods were increased to match the baseline diet's ounce equivalents of total protein foods. Matching instead the calories from protein foods requires a small additional increase in plant-based foods. Further, the ratio of the plant-based protein food groups (legumes : soy products : nuts) in the scenario diet is an unknown; we chose to set a normative ratio based on the vegetarian dietary pattern in the Dietary Guidelines for Americans. If we instead choose to maintain the ratio of these plant-based protein food groups as they appear in the 2016 baseline diet (far less soy products), the resulting emissions decrease somewhat because the emission factors for legumes and nuts are lower than soy products. As the composition of "soy products" (soy flour, soy concentrates, tofu) is not readily available in dietary recall summary tables, we represent soy products with soy protein isolate (SPI) in scenario 3. This option was chosen because SPI has a relatively high emission factor per kg for a plant-based food. While tofu has a lower emission factor per kg, because of the higher protein concentration in SPI, the emissions per kg of protein (as well as per ounce equivalent of protein food) are actually higher for tofu than for SPI. Therefore, when tofu is chosen to represent "soy products", the resulting emissions actually increase. A scenario where part of the dairy foods are replaced with almond milk (rather than all soymilk) has very little influence on the carbon footprint because a) the grams per cup equivalent is assumed the same for almond and soy milk and b) the difference in emission factors for almond and soy milk is small.

Table B-1. Summary of alternative modeling scenarios and their influence on diet-level GHGE

	Protein food target	Plant protein ratio	Soy product proxy	Plant-based dairy subst.	Diet GHGE (kg CO_2eq /capita/year)	Change from Scenario 3 result
Scenario 3	ounce-eq.	normative	SPI	100% soymilk	1189.1	
Alt 1	calories	normative	SPI	100% soymilk	1206.3	1.4%
Alt 2	ounce-eq.	baseline	SPI	100% soymilk	1143.9	-3.8%
Alt 3	calories	baseline	SPI	100% soymilk	1152.8	-3.1%
Alt 4	ounce-eq.	normative	tofu	100% soymilk	1231.6	3.6%
Alt 5	ounce-eq.	normative	SPI	75% almond milk, 25% soymilk	1175.6	-1.1%

Table B-2. Per capita availability of substituted plant-based foods using the baseline diet's ratio (Alt 2) compared to the normative ratio (scenario 3)

	Per capita availability (lbs/capita/year)	
	Scenario 3 (normative ratio)	Alt 2 (baseline ratio)
nuts	21.0	28.8
soy products	23.0	3.1
legumes	13.8	23.4