Diet, Energy, and Global Warming

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ABSTRACT: The energy consumption of animal- and plant-based diets and, more broadly, the range of energetic planetary footprints spanned by reasonable dietary choices are compared. It is demonstrated that the greenhouse gas emissions of various diets vary by as much as the difference between owning an average sedan versus a sport-utility vehicle under typical driving conditions. The authors conclude with a brief review of the safety of plant-based diets, and find no reasons for concern.

KEYWORDS: Diet; Energy consumption; Public health

1. Introduction

As world population rises (2.5, 4.1, and 6.5 billion individuals in 1950, 1975, and 2005, respectively; United Nations 2005), human-induced environmental pressures mount. By some measures, one of the most pressing environmental issues is global climate change related to rising atmospheric concentrations of greenhouse gases (GHGs). The link between observed rising atmospheric concentrations of CO_2 and other GHGs, and observed rising global mean temperature and other climatic changes, is not unequivocally established. Nevertheless, the accumulating evidence makes the putative link harder to dismiss. As early as 2000, the United Nations–sponsored Intergovernmental Panel on Climate Change (Houghton et al. 2001) found the evidence sufficiently strong to state that "there is new and stronger

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evidence that most of the warming observed over the last 50 years is attributable to human activities" and that "[t]he balance of evidence suggests a discernible human influence on global climate."

If one views anthropogenic climate change as an undesirable eventuality, it follows that modifying the ways we conduct various aspects of our lives is required in order to reduce GHG emissions. Many changes can realistically only occur following policy changes (e.g., switching some transportation volume to less CO_2-intensive modes). However, in addition to policy-level issues, energy consumption is strongly affected by individual personal, daily-life choices. Perhaps the most frequently discussed such choice is the vehicle one drives, indeed a very important element of one's planetary footprint. As we show below, an important albeit often overlooked personal choice of substantial GHG emission consequences is one's diet. Evaluating the implications of dietary choices to one's planetary footprint (narrowly defined here as total personal GHG emissions) and comparing those implications to the ones associated with personal transportation choices are the purposes of the current paper.

2. Comparative energy consumption by food production

In 1999, Heller and Keoleian (2000) estimated the total energy used in food production (defined here as agricultural production combined with processing and distribution) to be 10.2×10^{15} BTU yr^{-1}. Given a total 1999 U.S. energy consumption of 96.8×10^{15} BTU yr^{-1} (Table 1.1 in U.S. Department of Energy 2004a), energy used for food production accounted for 10.5% of the total energy used. In 2002, the food production system accounted for 17% of all fossil fuel use in the United States (Horrigan et al. 2002). For example, Unruh (2002) states that delivered energy consumption by the food industry, 1.09×10^{18} J in 1998, rose to 1.16×10^{18} J in 2000 and is projected to rise by 0.9% yr^{-1}, reaching 1.39×10^{18} J in 2020. Unruh (2002) also reports that delivered energy consumption in the crops and other agricultural industries (the latter consisting of, e.g., animal and fishing) increases, on average, by 1% and 0.9% yr^{-1}, respectively. Thus, food production, a function of our dietary choices, represents a significant and growing energy user.

To place energy consumption for food production in a broader context, we compare it to the more often cited energy sink, personal transportation. The annual U.S. per capita vehicle miles of travel was 9848 in 2003 (Table PS-1 in U.S. Department of Transportation 2004). Using the same source, and focusing on cars (i.e., excluding buses and heavy commercial trucks), per capita vehicle miles traveled becomes 8332, of which an estimated 63% are traveled on highways (Table VM-1 U.S. Department of Transportation 2004). According to the U.S. Department of Energy's (2005) table of most and least efficient vehicles (http://www.fueleconomy.gov/feg/best/bestworstNF.shtml) and considering only highly popular models, the 2005 vehicle miles per gallon (mpg) range is bracketed by the Toyota Prius' 60:51 (highway:city) on the low end and by Chevrolet Suburban's 11:15. At near average is the Toyota Camry Solara's 24:33 mpg. The salient transportation calculation (Table 1) demonstrates that, depending on the vehicle model, an American is likely to consume between 1.7×10^7 and 6.8×10^7 BTU yr^{-1} for personal transportation. This amounts to emissions of 1.19–4.76 ton CO_2

Table 1. Energy consumption for personal travel.

	Miles per gallon			Annual consumption		
Model	City	Highway	Weighted average[a]	Gallons	10^7 BTU[b]	Ton CO_2[c]
Prius	51	60	57	146	1.7	1.19
Camry	24	33	30	278	3.2	2.24
Suburban	11	15	14	595	6.8	4.76

[a] Based on 63% highway driving.

[b] The conversion of gallons consumed to BTU consumed is based on an average of 1 U.S. gallon of fuel = 115 000 BTU. Many sources report a conversion factor of 1 U.S. gallon of fuel = 125 000 BTU, but this assumes a so-called high heating value, which is not appropriate for motor vehicles' internal combustion engines [Oak Ridge National Laboratory bioenergy conversion factors; http://bioenergy.ornl.gov/papers/misc/energy_conv.html].

[c] The conversion of BTU consumed to CO_2 emissions is based on the total of the U.S. emissions, as described in the text.

based on the estimated conversion factor of 7×10^{-8} ton CO_2 BTU^{-1} derived from the 2003 U.S. total energy consumption, 98.6×10^{15} BTU (U.S. Department of Energy 2004a), and total CO_2 emissions of 6935.9×10^6 ton (U.S. Department of Energy 2004b).

Next, we perform a similar energetic calculation for food choices. Accounting for food exports, in 2002 the U.S. food production system produced 3774 kcal per person per day or 1.4×10^{15} BTU yr^{-1} nationwide (FAOSTAT 2005). (The difference between 3774 kcal per person per day and the needed average ~2100 kcal per person per day is due to overeating and food discarded after being fully processed and distributed.) In producing those 1.4×10^{15} BTU yr^{-1}, the system used 10.2×10^{15} BTU yr^{-1}. That is, given both types of inefficiency, food production energy efficiency is $100(1.4/10.2)(2100/3774) \approx 7.6\%$. Therefore, in order to ingest 2100 kcal day^{-1}, the average American uses $2100/0.076 \approx 72.6 \times 10^4$ kcal day^{-1} or

$$2100\frac{\text{kcal}}{\text{day}} \times \frac{1\ \text{BTU}}{0.252\ \text{kcal}} \times 365\frac{\text{day}}{\text{yr}} \times \frac{1}{0.076} \approx 4 \times 10^7\,\frac{\text{BTU}}{\text{yr}}. \qquad (1)$$

In summary, while for personal transportation the average American uses 1.7×10^7 to 6.8×10^7 BTU yr^{-1}, for food the average American uses roughly 4×10^7 BTU yr^{-1}. Thus, there exists an order of magnitude parity in fossil energy consumption between dietary and personal transportation choices. This is relevant to climate because fossil fuel–based energy consumption is associated with CO_2 emissions. Note that both food production and transportation also release non-CO_2 GHGs produced during fossil fuel combustion (principally NO_x conversion to N_2O), but these are ignored below. This omission is irrelevant to the comparison between transportation and food production because these contributions are proportional to the mass of fossil fuel burned and thus scale with CO_2 emissions. They are noteworthy, however, as they render our bottom-line conclusion an underestimate of the range of GHG burden resulting from dietary choices.

The next logical step is quantifying the range of GHG emissions associated with various reasonable dietary choices. In exploring this question, we note that food production also releases non-CO_2 GHGs *un*related to fossil fuel combustion (e.g., methane emissions due to animal manure treatment). In comparing below the GHG burden exerted by various reasonable dietary choices we take note of both contributions.

3. Plant-based versus animal-based diets

To address the variability in energy consumption and GHG emissions for food, we focus on a principal source of such variability, plant- versus animal-based diets. To facilitate a quantitative analysis, we define and consider several semirealistic mixed diets: mean American, red meat, fish, poultry, and lacto-ovo vegetarian. These diets are shown schematically in Figure 1. To obtain the mean American

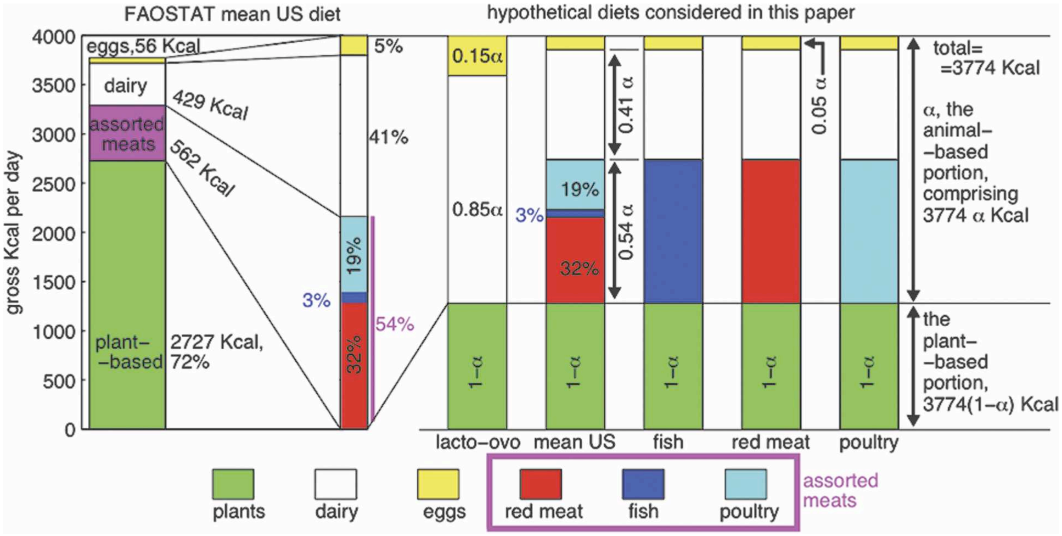

Figure 1. The composition of the diets discussed in this paper. (left) The actual observed mean U.S. diet based on per capita food disappearance data (FAOSTAT 2005). The legend at the bottom shows the various components. The mean diet comprises 3774 gross kcal, of which 1047 kcal are from animal products. The breakdown of the animal-based portion, shown on the right side of the panel, is 54% meats, 41% dairy, and 5% eggs. (right) Schematic depiction of the five semirealistic, hypothetical diets considered in this paper, all comprising 3774 kcal. The (variable) fraction of the total from animal products, α (shown on the right end of the plot), comprises the various animal-based food items shown and totals $3774a$ kcal. The remaining plant-based portion totals $3774(1 - a)$ kcal. Of the animal-based part of the lacto-ovo diet, 85% of the calories are from dairy, and 15% from eggs. In the remaining four diets (mean American, fish, red meat, and poultry), 46% of the animal-based calories are from dairy and eggs, similar to the observed mean American diet shown in the left panel, with the remaining 54% from either the single sources shown, or the blend of sources characterizing the mean American diet. Red meat consists of 35.61% beef, 62.61% pork, and 1.78% lamb.

diet, we use actual per capita food supply data summarized in the Food Balance Sheets for 2002 (FAOSTAT 2005). Those balance sheets report a total gross caloric consumption of 3774 kcal per person per day, of which 1047 kcal, or 27.7%, is animal based. Of those 1047 kcal day^{-1}, 41% are derived from dairy products, 5% from eggs, and the remaining 54% from various meats. For comparison, we let all diets, including the exclusively plant-based one ("vegan"), comprise the same total number of gross calories, 3774 kcal day^{-1}.

The red meat, fish, and poultry diets we consider share similar dairy and egg portions, 41% and 5% of the animal-based caloric fraction of the diet (Figure 1). The remaining 54% of the animal-based portion of the diet is attributed to the sole source given by the diet name. For example, the animal-based part of the red meat diet comprises 41%, 5%, and 54% of the animal-based calories from dairy, eggs, and red meat, respectively. For the purposes of this paper, we define red meat as comprising 35.6% beef, 62.6% pork, and 1.8% lamb, reflecting the proportions of these meats in the FAOSTAT data. In the lacto-ovo diet, we set the total animal-based energy derived from eggs and dairy to 15% and 85% based on values from Table 1 of Pimentel and Pimentel (2003).

Specific diets vary widely in the fraction of caloric input from animal sources (hereafter α). For example, Haddad and Tanzman (2003) suggest that lacto-ovo vegetarian diets in the United States contain less than 15% of their calories from animal sources, well below the 27.7% derived from animal sources in the mean American diet. We therefore calculate the energy and GHG impact of each diet over a range of this fraction, $0\% \leq a \leq 50\%$, where $\alpha = 0$ corresponds to a vegan diet.

3.1. Greenhouse effects of direct energy consumption

This section addresses the greenhouse burden by agriculture that is directly exerted through (mostly fossil fuel) energy consumption and the subsequent CO_2 release. The fossil fuel inputs treated here are related to direct energy needs such as irrigation energy costs, fuel requirements of farm machinery, and labor. We are interested in the range of this burden affected by dietary choices, especially plant- versus animal-based diets.

We define energy efficiency as the percentage of fossil fuel input energy that is retrieved as edible energy [$e = 100 \times$ (output edible energy)/(fossil energy input); see Table 2]. We derive energy efficiency e of various animal-based food items by combining available estimates of (edible energy in protein output)/(fossil energy input) (Pimentel and Pimentel 1996a) and the total energy content relative to the energy from protein. The estimated energy efficiency of protein in animal products (Pimentel and Pimentel 1996a) varies from 0.5% for lamb to ~5% for chicken and milk to 3% for beef (second column of Table 2). This wide range reflects the different reproductive life histories of various animals, their feed, their genetic ability to convert nutrients and feed energy into body protein, fat, and offspring, the intensity of their rearing, and environmental factors (heat, humidity, severe cold) to which they are subjected, among other factors. Accounting for the total energy content relative to the energy from protein (Table 2; U.S. Department of Agriculture 2005), these numbers translate to roughly 1%, 20%, and 6% ($e = 0.1$, 0.2, and 0.06). The weighted mean efficiency of meat [red meat (consisting of

Table 2. Energetic efficiencies for a few representative food items derived from land animals, aquatic animals, and plants.

Food item	$100 \times \frac{\text{kcal protein}}{\text{kcal input}}$[a]	$\frac{\text{kcal total}}{\text{kcal protein}}$[b]	$100 \times \frac{\text{kcal output}}{\text{kcal input}}$[c]
Livestock			
Chicken	6.3	2.9	18.1
Milk	5.3	3.9	20.6
Eggs	3.6	3.1	11.2
Beef (grain fed)	2.9	2.3	6.4
Pork	1.5	2.5	3.7
Lamb	0.5	2.3	1.2
Fish			
Herring	50.0	2.2	110
Tuna	5.0	1.2	5.8
Salmon (farmed)	2.5	2.3	5.7
Shrimp	0.7	1.3	0.9
Plants			
Corn			250
Soy			415
Apple			110
Potatoes			123

[a] Pimentel and Pimentel (1996a,b); energy input refers to fossil fuels.

[b] Assuming 1 gram protein = 4 kcal and using U.S. Department of Agriculture (2005) values.

[c] For animal products, the product of the previous two columns.

beef, pork, and lamb, as previously defined), fish, and poultry] in the American diet is 9.32% (U.S. Department of Agriculture 2002; see Table 3). These efficiencies are readily comparable with the energy efficiency f of plant-based foods estimated by Pimentel and Pimentel (1996b,c): 60% for tomatoes, ~170% for oranges and potatoes, and 500% for oats. The wide range of f reflects differences in farming intensity, including labor, machinery operation, and synthetic chemical requirements.

Table 3. Weighted-mean energetic efficiency of the animal-based portion of the hypothetical mixed diets considered in this paper.

Diet	Component	Percent efficiency	Caloric fraction	Weighted mean (%)
Lacto-ovo	Dairy	20.6	0.85α	19.19
	Eggs	11.2	0.15α	
Mean American	Dairy	20.6	0.41α	14.05
	Eggs	11.2	0.05α	
	Meat	9.3	0.54α	
Fish	Dairy	20.6	0.41α	11.52
	Eggs	11.2	0.05α	
	Fish	4.6	0.54α	
Red meat	Dairy	20.6	0.41α	11.52
	Eggs	11.2	0.05α	
	Meat	9.3	0.54α	
Poultry	Dairy	20.6	0.41α	18.76
	Eggs	11.2	0.05α	
	Poultry	9.3	0.54α	

Because of the wide range of efficiencies in both plant- and animal-based foods, we quantitatively compare plant-based diets with animal-based ones by considering

$$E = cd\left(\frac{\alpha}{e} + \frac{1-\alpha}{f}\right) \tag{2}$$

for the various hypothetical diets shown in Figure 1. In (2),

$$c = 3774\frac{\text{kcal}}{\text{day}} \times 365\frac{\text{day}}{\text{yr}} \approx 1\,377\,510\frac{\text{kcal}}{\text{yr}}$$

is the U.S. per capita annual gross caloric consumption, and

$$d = \frac{1}{0.252}\frac{\text{kcal}}{\text{BTU}} \times (7 \times 10^{-8})\,\frac{\text{ton CO}_2}{\text{BTU}} \approx 2.778 \times 10^{-7}\,\frac{\text{ton CO}_2}{\text{kcal}},$$

so that $cd \approx 0.383$ ton CO_2 yr^{-1} is the annual CO_2 emissions of a person consuming 3774 kcal day^{-1} using the BTU–CO_2 conversion factor introduced earlier and assuming perfect efficiency (the deviation from ideal efficiency is accounted for by the bracketed term). The parameter α is the fraction of the dietary caloric intake derived from animal sources. As defined above, e and f are the weighted mean caloric efficiencies of animal- and plant-based portions of a given diet. Those efficiencies for the five hypothetical diets considered here, shown in Table 3, are simply the weighted mean efficiencies derived from the characteristic caloric efficiency of each component of the diet and the caloric prevalence of those components.

The efficiencies are $e = 0.1152$ (fish), 0.1152 (red meat), 0.1405 (average American diet), 0.1876 (poultry), and 0.1919 (lacto-ovo). Recall that the red meat, mean American, fish, and poultry diets derive 41% and 5% of their animal-based calories from dairy and eggs; thus, the weighted-mean efficiency e of the diets reflects the higher efficiency of dairy and egg relative to fish or red meats. The specific (not weighted mean) efficiency of poultry production is between those of dairy and eggs (Table 2). The notable equality of fish and red meat efficiencies reflects 1) the large energy demands of the long-distance voyages required for fishing large predatory fishes such as swordfish and tuna toward which western diets are skewed, and 2) the relatively low energetic efficiency of salmon farming. Note that similar e values for two or more diets (such as the poultry and lacto-ovo above) reflect similar overall energetic efficiency of the total diets only if those diets also share α, the animal-based caloric fraction of the diet. However, recall the aforementioned Haddad and Tanzman (2003) suggestion that American lacto-ovo vegetarians eat less than 15% of their calories from animal sources, indicating that the overall energetic efficiency of lacto-ovo diets is higher than that of the average poultry diet assumed here, with $\alpha = 0.277$, the same fraction as that of the mean American diet.

Equation (2) allows us to calculate the total CO_2 burden related to fossil fuel combustion for various diets characterized by specific α, e, and f values. However, our objective is to compute the difference between various mixed diets and an exclusively plant-based, vegan, diet. To facilitate such comparison, we get an expression for the difference in CO_2-based footprint between mixed diets and an exclusively plant-based one by subtracting from Equation (2) the expression for a purely plant-based diet. We get the latter by setting $\alpha = 0$ in Equation (2), yielding $E_{\text{vegan}} = cd/f$, with which

$$\delta E \equiv E - E_{\text{vegan}} = c\, d\, \alpha \left(\frac{1}{e} - \frac{1}{f}\right). \tag{3}$$

Figure 2 shows the results of solving Equation (3) with $0 \leq a \leq 0.5$ for three values of e corresponding to fish and red meat (red), poultry/lacto-ovo (magenta), and the blend of animal sources characteristic of the average American diet (blue). For each value of e (each color), we solve for δE with the three shown values of f, bracketing the actual efficiency of nearly all plant-derived foods.

Note that the difference among the three diet groups is larger than the range in efficiencies arising from different values of f for a given mean e. Figure 2 shows that a person consuming the average American diet, with average caloric efficiencies of the animal- and plant-based portions of the diet, releases 701 kg of CO_2 yr^{-1} beyond the emissions of a person consuming only plants. Compared with driving

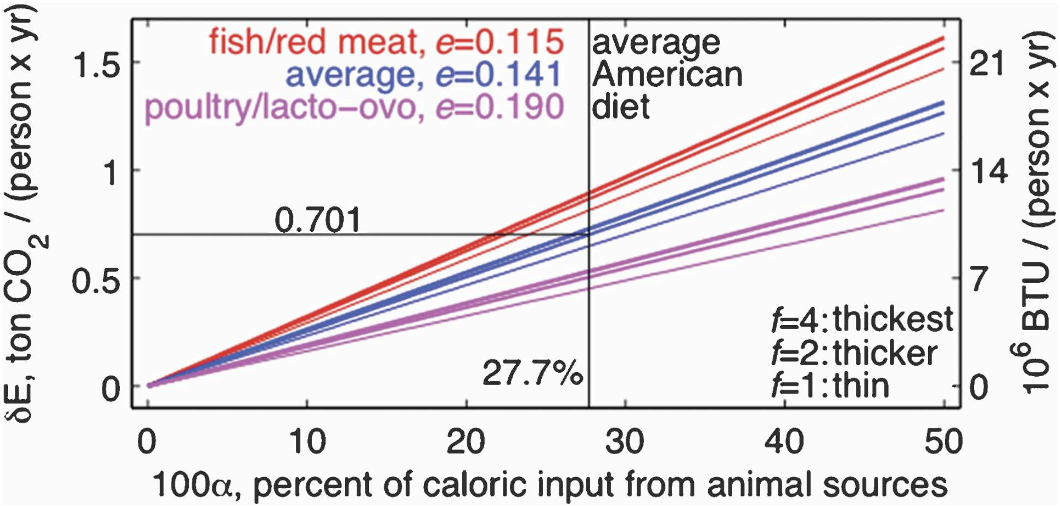

Figure 2. Comparison of four mixed diets to an exclusively plant-based one in terms of additional energy use beyond that of the plant-based diet. The additional energy use per person per year is reported in two interchangeable units, tons of CO_2 emissions on the left, and million BTUs on the right, using the conversion factor introduced in the text. The four animal-based diets considered are shown in the upper left. The blue curves show the average animal-based diet composition, with caloric efficiency of e = 13.7%. For each diet (a given color), three curves are shown, differing from each other in the caloric efficiency of the plant-based fraction of the diet, f, where the values considered are 1.2, 2, and 4. The average American diet, with α = 0.277 (with 27.7% of calories from animal sources) is shown, along with the added CO_2 it corresponds to (assuming average efficiency of 13.7%), 0.726 ton.

a Toyota Camry under the conditions of Table 1, this amounts to 100 × 0.701/2.24 ≈ 31.3%, that is, roughly a third of the greenhouse costs of personal transportation.

3.2. Greenhouse effects in addition to energy inputs

Of agriculture's various non-energy-related GHG emissions, we focus below on the two main non-CO_2 GHGs emitted by agriculture, methane, CH_4, and nitrous oxide, N_2O. In 2003, U.S. methane emissions from agriculture totaled 182.8×10^6 ton CO_2-eq, of which 172.2×10^6 ton CO_2-eq are directly due to livestock (U.S. Department of Energy 2004b). The same report also estimates the 2003 agriculture-related nitrous oxide emissions, 233.3×10^6 ton CO_2-eq, of which 60.7×10^6 ton CO_2-eq are due to animal waste. Thus, the production of livestock in the U.S. emitted methane and nitrous oxide is equivalent to at least $172.2 \times 10^6 + 60.7 \times 10^6 = 232.9 \times 10^6$ ton CO_2 in 2003. With 291 million Americans in 2003, this amounts to 800 kg CO_2-eq per capita annually in excess of the emissions associated with a vegan diet.

One may reasonably argue that the ~0.8 ton CO_2-eq per person per year due to non-CO_2 GHGs does not accurately represent the difference between animal- and plant-based diets, which is our object of inquiry; if there were no animal-based food production at all, plant-based food production would have to increase. However, such a hypothetical transition will produce zero methane and nitrous oxide emissions in the categories considered above, animal waste management, and enteric fermentation by ruminants. Ignored categories, principally soil management, will indeed have to increase, but over an area far smaller than that vacated by eliminating feed production for animals. For example, Reijnders and Soret (2003) report that, per unit protein produced, meat production requires 6 to 17 times as much land as soy. Therefore, the net reduction in methane and nitrous oxide emissions will have to be larger than our estimate presented here.

Approximately 74% of the total nitrous oxide emissions from agriculture, $\sim 173 \times 10^6$ ton CO_2-eq, are due to nitrogen fertilization of cropland, which supports production of both animal- and plant-based foods. The exact partitioning of nitrogen fertilization into animal feed and human food is a complex bookkeeping exercise beyond the scope of this paper. Consequently, we ignore this large contribution below. Nevertheless, simple analysis of the Food Balance Sheets (FAOSTAT 2005) and Agriculture Production Database (FAOSTAT 2005) data shows that the portion of those 173×10^6 ton CO_2-eq attributable to animal production is at least equal to, and probably larger than that attributable to plants, thereby rendering our estimate of the GHG burden exerted by animal-based food production a lower bound.

The value of 800 kg CO_2-eq yr^{-1} due to non-CO_2 emissions computed above represents the composition of the actual mean American diet. To calculate the added non-CO_2 burden of specific diets, we must first compute, from the mean American diet, the burden for individual food items.

This calculation requires intermediate steps, as available data are for specific farm animals, not individual food items. Using annual emissions reported by the U.S. Department of Energy (2004b), in Table 4 we sum the contributions of methane from enteric fermentation and manure management and the nitrous oxide

Table 4. Non-CO_2 GHG emissions associated with the production of various food items. Units are 10^6 CO_2-eq yr^{-1}, except column 6.

	CH_4^a				
Food	Enteric fermentation	Manure management	N_2O* manure management	Sum	Approx percentage of total
Eggs	—	2.08	0.62	2.70	1
Dairy	26.68	18.18	21.96	66.82	29
Beef	82.04	4.43	34.34	120.81	56
Pork	2.07	30.20	1.70	33.97	15
Poultry	—	2.31	0.68	2.99	1
Sheep	1.16	0.03	0.60	1.79	1
Goats	0.14	0.01	0.20	0.35	<1
				Total: 229.41	

* Sources: U.S. Department of Energy (2004b, Tables 21, 22, and 28).

from manure management for cattle, pigs, poultry, sheep, and goats. To partition cattle methane emissions from enteric fermentation [108.72 million ton CO_2-eq; Table 21 in U.S. Department of Energy (2004b)] among beef (75.46%) and dairy (24.54%) cattle, we use emission ratios derived from Table 5-3 of U.S. Environmental Protection Agency (2005) (we apply these ratios to the 2003 data, but we do not use the absolute values, because the table's latest entry is 2001). We similarly use Table 5-5 of U.S. Environmental Protection Agency (2005) to partition nitrous oxide emissions from cattle manure management, 56.3 million ton CO_2-eq [Table 28 in U.S. Department of Energy (2004b)], among dairy (39%) and beef (61%) cattle.

Table 28 in U.S. Department of Energy (2004b) reports emissions of 1.3 million ton CO_2-eq from N_2O due to poultry manure management. Because we do not have direct information on the partitioning of these emissions among eggs and poultry meat, we assume this partition in N_2O is proportional to total manure mass and thus is roughly similar to the partitioning of methane from poultry manure management, 47.38% and 52.62% for eggs and meat, respectively (Table 22 in U.S. Department of Energy 2004b). We thus partition the 1.3 million ton CO_2-eq from N_2O due to poultry manure management as 0.62 and 0.68 million ton CO_2-eq due to eggs and poultry meat, respectively.

To obtain the per capita daily emissions associated with food items, we divide the individual non-CO_2 GHG annual sums (Table 4, fourth numeric column) by the U.S. 2003 population, 291 million, and 365 days. The results, in grams of CO_2-eq per day, are shown in the first numeric column in Table 5. To calculate emissions per kcal associated with the consumption of individual food items, we divide the per capita daily emissions (Table 5, first numeric column) by the respective per capita consumptions (FAOSTAT 2005; Table 5, second numeric column). These divisions yield the non-CO_2 GHG emissions per kcal reported in the rightmost column in Table 5. Importantly, the non-CO_2 GHG emissions per kcal vary by as much as a factor of 70 for the animal-based food items considered, rendering some animal-based options (e.g., poultry meat) far more benign than other ones (most notably beef).

Using the emission associated with individual food items (Table 5, rightmost

Table 5. Non-CO_2 GHG emissions per unit food consumed, derived from the actual mean American diet in the Food Balance Sheets (FAOSTAT 2005).

Food	Per capita emissions, gram CO_2-eq day^{-1}*	Per capita consumption in mean American diet, kcal day^{-1}	Emissions gram CO_2-eq kcal
Dairy + butter	629.1	429	1.47
Eggs	25.4	56	0.45
Beef	1137.4	120	9.48
Pork + fat	319.8	211	1.52
Poultry	28.2	196	0.14
Sheep	16.9	6	2.82
Fish	—	29	0.00
Total		1047	

* Results from dividing the "sum" column in Table 5 (FAOSTAT 2005) by 291 million Americans and 365 days.

column), we calculate the weighted non-CO_2 GHG emissions for the *i*th hypothetical diet considered in this paper,

$$\beta_i = \sum_{j=1}^{M} \begin{bmatrix} \text{individual daily} \\ \text{emissions of} \\ \text{component } j \\ \text{in diet } i, \\ \text{grams CO}_2\text{-eq kcal}^{-1} \end{bmatrix} \times \begin{bmatrix} \text{daily} \\ \text{kcals of} \\ \text{component} \\ j \text{ in diet } i \end{bmatrix} \sim \frac{\text{grams CO}_2\text{-eq}}{\text{kcal}}, \tag{4}$$

where M is the number of food items diet i comprises. In calculating β for the red meat and mean American diets, we sum the emissions due to individual meat items. The composition of the mean American diet is detailed in Table 5. The composition of meat in the red meat diet is 35.6% beef, 62.6% pork, and 1.8% lamb, as defined in section 3. The βs of the various diets are computed, using Equation (4) in Table 6.

Using β we modify Equation (3) to take note of both CO_2 and non-CO_2 GHG emissions,

$$\delta E_i = c\ \alpha_i \left[d\left(\frac{1}{e_i} - \frac{1}{f_i}\right) + 10^{-6}\beta_i \right], \tag{5}$$

where the 10^{-16} factor is needed to convert from grams to tons. Figure 3 summarizes the GHG burden exerted by animal-based food production through both CO_2 emissions due to fossil fuel combustion and non-CO_2 (methane and nitrous oxide) emissions. Adding the non-CO_2 GHG emissions more than doubles the impact of the mean American diet at mean (27.7%) animal fraction, from 701 kg CO_2-eq per person per year in Figure 2 based on fossil fuel input alone to nearly 1.5 ton CO_2-eq per person per year in Figure 3 taking note of fossil fuel inputs as well as non-CO_2 emissions. Recall that this is an underestimate of the actual radiative

Table 6. Non-CO_2 GHG emissions of the hypothetical diets considered in this paper.

Diet	Component	Individual emissions $\frac{\text{gram } CO_2\text{-eq}}{\text{kcal}}$	Caloric fraction	β, $\frac{\text{gram } CO_2\text{-eq}}{\text{kcal}}$
Lacto-ovo	Dairy	1.47	0.85α	
	Eggs	0.45	0.15α	1.317
Mean American	Dairy	1.47	0.41α	
	Eggs	0.45	0.05α	
	Meat*	2.67	0.54α	2.067
	Dairy	1.47	0.41α	
Fish	Eggs	0.45	0.05α	
	Fish	0.00	0.54α	0.625
Red meat	Dairy	1.47	0.41α	
	Eggs	0.45	0.05α	
	Meat**	4.43	0.54α	3.017
	Dairy	1.47	0.41α	
Poultry	Eggs	0.45	0.05α	
	Poultry	0.14	0.54α	0.701

* Beef 21.35%, pork 37.54%, lamb 1.07%, poultry 34.88%, fish 5.16%; the actual emissions are detailed in the third numeric column of Table 5.

** Beef 35.61%, pork 62.61%, and lamb 1.78%.

effect of an animal-based diet relative to a plant-based one because of the neglect of land management in the nitrous oxide budget and other conservative idealizations we have made.

In addition to amplifying the GHG burden of all mixed diets, the added inclusion of non-CO_2 GHGs reveals several consequences of dietary choices. First, red meat and fish diets, which previously coincided because the only consideration was caloric efficiency e, which is roughly 0.11 for both, are now clearly distinct. Second, with the effect of non-CO_2 GHGs included, the fish diet results in lower GHG emissions than both the red meat and mean American diets. This is partly attributable to our choice to ignore small non-CO_2 GHG emissions associated with fish consumption. Third, the lacto-ovo vegetarian diet appears to result in higher GHG emissions than the poultry diet. According to our calculations this is true for any α; however, if lacto-ovo vegetarians eat less than average animal products, as suggested by Haddad and Tanzman (2003), the relevant comparison is not for a given α (a vertical line in Figure 3), but rather between one α for lacto-ovo diet, for example, $\alpha \approx 0.15$, and a higher one for poultry, for example, $\alpha \approx 0.27$.

To place the planetary consequences of dietary choices in a broader context, note that at mean U.S. caloric efficiency (blue line in Figure 3), it only requires a dietary intake from animal products of ~20%, well below the national average, 27.7%, to increase one's GHG footprint by an amount similar to the difference between an ultraefficient hybrid (Prius) and an average sedan (Camry). For a person consuming a red meat diet at ~35% of calories from animal sources, the added GHG burden above that of a plant eater equals the difference between driving a Camry and an SUV. These results clearly demonstrate the primary effect of one's dietary choices on one's planetary footprint, an effect comparable in magnitude to the car one chooses to drive.

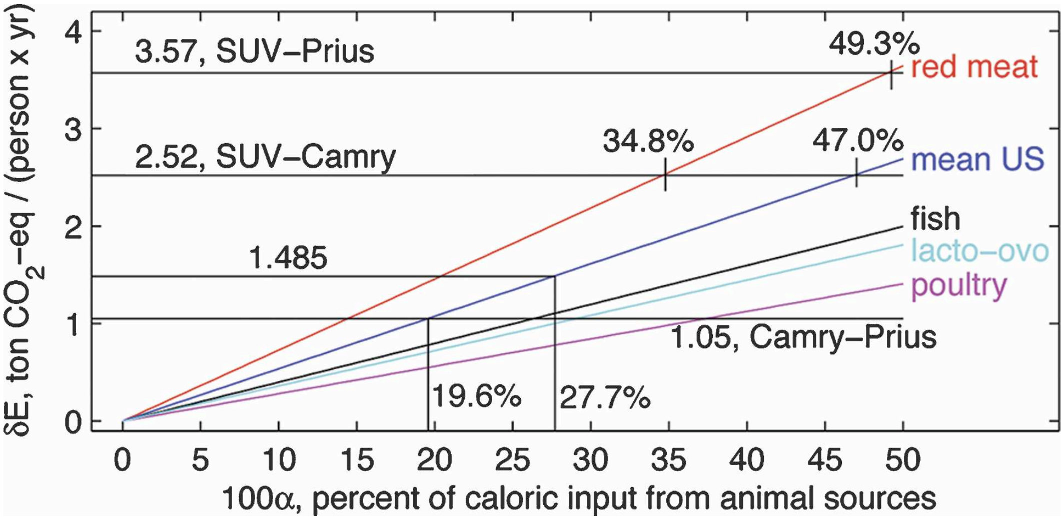

Figure 3. The greenhouse burden (considering CO_2, N_2O, and CH_4) exerted by various plant- and animal-based diets. Each of the five lines represents a semirealistic mixed diet. All five diets have the same caloric intake, and all are considered for animal portion of calories, α, in the range 0%–50%. The differences in GHG burden among various car models are shown; e.g., the difference between a Toyota Camry and a Prius, 1.05 ton CO_2 per person per year, is the lowermost horizontal dotted line. The percent of animal-based product in various diets that must be consumed to equal those added burdens are also shown with vertical tick marks. For example, the added GHG emissions associated with the difference between a red meat diet and a plant-based one is comparable to the difference between a Toyota Camry and an SUV, 2.52 ton CO_2 per person per year, when the portion of animal-based calories in the diet is 26%. While the blue curve involves only caloric efficiency, and therefore can span the entire α range, the mean composition, 27.7% of calories from animal sources, is shown by the vertical gray line, along with the added GHG burden associated with this diet, ~1.5 ton CO_2 per person per year.

4. Are plant-based diets safe?

The thrust of this paper has been that the United States bears a GHG burden for the animal-based portion of its collective diet. From Figure 3 we can estimate this burden as roughly 1.485 ton CO_2-eq per person per year × 291 million Americans ≈ 432 million ton CO_2-eq yr^{-1} nationwide, or ~6.2% of the total [69 335.7 million ton CO_2-eq in 2003 (Table ES2 of U.S. Department of Energy 2004b)]. To the extent one subscribes to the notion that reducing GHG emissions is desirable, a corollary of this estimate is that it is advantageous to minimize the animal-based portion of the mean American diet. This raises the question of whether a plant-based diet is nutritionally adequate for public health. The following section addresses this question. The available evidence suggests that plant-based diets are safe, and are probably nutritionally superior to mixed diets deriving a large fraction of their calories from animals.

The adverse effects of dietary animal fat intake on cardiovascular diseases is by now well established (see Willett 2001 for a comprehensive review). Similar effects are also seen when meat, rather than fat, intake is considered (e.g., Key et al. 1999; Erlinger and Appel 2003). Less widely appreciated—despite being just as persuasively demonstrated, exhaustively researched, and robustly reproducible—are the links between animal protein consumption and cancer (for a thorough review, see Campbell and Campbell 2004).

The first studies linking dietary animal protein and cancer (e.g., Mgbodile and Campbell 1972; Preston et al. 1976) focused on cancer initiation, the brief process during which cancer-causing mutations first occur. Collectively, they documented numerous cellular mechanisms by which cancer initiation increases under high animal protein diets. Follow-up studies (e.g., Appleton and Campbell 1982; Dunaif and Campbell 1987) addressed cancer promotion after initiation, showing dramatically increased precancerous deformities in response to a given carcinogen dose under high animal protein diets. To unambiguously implicate animal protein in the observed enhanced cancer promotion, Schulsinger et al. (1989) compared induced carcinogenesis under high protein diets of animal and plant origins. Cancer promotion was significantly enhanced under animal-protein-rich diet. Youngman (1990) and Youngman and Campbell (1992) extended these results to clinical cancer (as opposed to cancer precursors), showing roughly an order of magnitude higher tumor incidence in rats on high animal-protein diets who lived their full natural life span. Similar results were also obtained with different species and carcinogens (e.g., Cheng et al. 1997; Hu et al. 1997). Note that the above laboratory results were all obtained at protein intakes per unit body mass routinely consumed by Westerners, suggesting the applicability of the results to humans (Campbell and Campbell 2004).

Human epidemiological evidence indeed corroborates the link between animal-based diet and cancer. For example, Larsson et al. (2004) show enhancement of ovarian cancer with dairy consumption in Swedish women; Sieri et al. (2002) show a strong association between animal protein intake and breast cancer in Italian women; Chao et al. (2005) show a tight positive relationship between meat consumption and colorectal cancer; and Fraser (1999) demonstrates an approximate halving of colon and prostate cancer risk among vegetarians. Barnard et al. (1995) documented the disease burden exerted by seven major diseases on the health care system directly related to meat consumption. Some of the above cited results may well be challenged in the future. Nevertheless, it is hard to avoid the conclusion, reached by, for example, Sabate (2003), that animal-based diets discernibly increase the likelihood of both cardiovascular diseases and certain types of cancer. To our knowledge, there is currently no credible evidence that plant-based diets actually undermine health; the balance of available evidence suggests that plant-based diets are at the very least just as safe as mixed ones, and are most likely safer.

5. Conclusions

We examine the greenhouse gas emissions associated with plant- and animal-based diets, considering both direct and indirect emissions (i.e., CO_2 emissions due to fossil fuel combustion, and methane and nitrous oxide CO_2-equivalent emissions due to animal-based food production). We conclude that a person consuming a mixed diet with the mean American caloric content and composition causes the emissions of 1485 kg CO_2-equivalent above the emissions associated with consuming the same number of calories, but from plant sources. Far from trivial, nationally this difference amounts to over 6% of the total U.S. greenhouse gas emissions. We conclude by briefly addressing the public health safety of plant-based diets, and find no evidence for adverse effects.

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