Potential contributions of food consumption patterns to climate change[1–4]

Annika Carlsson-Kanyama and Alejandro D González

ABSTRACT
Anthropogenic warming is caused mainly by emissions of greenhouse gases (GHGs), such as carbon dioxide, methane, and nitrous oxide, with agriculture as a main contributor for the latter 2 gases. Other parts of the food system contribute carbon dioxide emissions that emanate from the use of fossil fuels in transportation, processing, retailing, storage, and preparation. Food items differ substantially when GHG emissions are calculated from farm to table. A recent study of ≈20 items sold in Sweden showed a span of 0.4 to 30 kg CO_2 equivalents/kg edible product. For protein-rich food, such as legumes, meat, fish, cheese, and eggs, the difference is a factor of 30 with the lowest emissions per kilogram for legumes, poultry, and eggs and the highest for beef, cheese, and pork. Large emissions for ruminants are explained mainly by methane emissions from enteric fermentation. For vegetables and fruits, emissions usually are $\leq$2.5 kg CO_2 equivalents/kg product, even if there is a high degree of processing and substantial transportation. Products transported by plane are an exception because emissions may be as large as for certain meats. Emissions from foods rich in carbohydrates, such as potatoes, pasta, and wheat, are $<$1.1 kg/kg edible food. We suggest that changes in the diet toward more plant-based foods, toward meat from animals with little enteric fermentation, and toward foods processed in an energy-efficient manner offer an interesting and little explored area for mitigating climate change. *Am J Clin Nutr* 2009;89(suppl):1704S–9S.

INTRODUCTION

Anthropogenic emissions of greenhouse gases (GHGs) arise from a large variety of activities. Previous studies (1–3) have shown that choice of food and diet can influence the energy requirements for the provision of human nutrition and the associated GHG emissions. Meals similar in caloric content may differ by a factor of 2 to 9 in GHG emissions (1, 2). An analysis of the energy inputs required to produce a large number of food items showed that meals with similar nutritional value had a difference in GHG emissions of up to a factor of 4, depending on the items chosen (3). All of these studies identified certain foods as more resource demanding/polluting, including animal products and certain vegetable products produced in resource-intensive ways.

Current trends in food choices point toward increased environmental effects (4, 5). More environmentally friendly diets need to be identified. When environmental and health aspects of diets are considered, there is no apparent contradiction. Duchin (6), who studied diets from multiple viewpoints of sustainability, showed that a Mediterranean diet, which consists mainly of plant-origin foods but not excluding a small proportion of meat and other animal products, is closer to public health recommendations issued by the World Health Organization (www.who.net) and has a lower environmental effect than the current average US diet. Current agricultural policies may be counterproductive for achieving diets that are healthy and environmentally friendly (7). New agricultural policies are needed that consider a reduction of environmental effects as well as a shift toward improved public health and, in particular, a reduction of noncommunicable chronic diseases.

This review is organized as follows: first, a short overview of GHGs in food production systems; second, analysis of the total contribution of 22 food items to GHG emissions; and third, analysis of examples of simple meals to show the effect on GHG emission that food choices can make. We conclude by emphasizing that research is needed to understand why dietary change is not on the climate policy agenda.

GHGs IN FOOD PRODUCTION

According to the latest report of Working Group I of the Intergovernmental Panel on Climate Change (IPCC) (8), carbon dioxide is the most important anthropogenic GHG. The main source of human-induced emissions is the use of fossil fuels. Other gases, however, so-called non–carbon dioxide GHGs, also are important as drivers for climate change. For instance, methane is second to carbon dioxide when it comes to the overall contributions of *radiative forcing*. Radiative forcing is the change in the net irradiance in the tropopause due to external

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[1] From the Division of Industrial Ecology, Royal Institute of Technology, Stockholm, Sweden (AC-K), and the Research Institute on Biodiversity and Environment (Inibioma-Conicet), Bariloche, Argentina (ADG).

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[4] Reprints not available. Address correspondence to A Carlsson-Kanyama, Division of Industrial Ecology, Royal Institute of Technology, SE 100 44, Stockholm, Sweden. E-mail: annika@carlsson-kanyama.se.

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drivers such as concentrations of GHGs. Halocarbons are third and nitrous oxide is fourth in contributing to radiative forcing. Because the radiative properties of GHGs differ substantially, even small amounts of certain gases may cause significant change when emitted into the atmosphere. For example, on a molecule-to-molecule basis, nitrous oxide is ≈300 times more efficient than carbon dioxide. The global increase in methaneand nitrous oxide in the atmosphere is caused primarily by agriculture (9). Of global anthropogenic emissions in 2005, agriculture accounted for ≈60% of nitrous oxide and ≈50% of methane (10). The amount of such emissions from agriculture depends on production techniques, natural processes in soils, and animal metabolism. Substantial emissions of carbon dioxide also occur during mechanized agriculture because of fossil fuel requirements for inputs such as fertilizers and energy requirements during irrigation and other farming practices (11).

Regarding non–carbon dioxide GHGs, methane is produced when organic materials decompose in oxygen-deprived conditions, notably from fermentative digestion by ruminant livestock, from stored manures, and from rice grown under flooded conditions (10, 12). Emissions of this gas, therefore, can be tied to products such as meat, milk, and rice. Nitrous oxide is generated by the microbial transformation of nitrogen in soils and manures and often is enhanced where available nitrogen exceeds plant requirements, especially under wet conditions (10, 12). Emissions of nitrous oxide, therefore, can be tied to any crop grown under these conditions and to animal products. Emissions of nitrous oxide also occur when synthetic nitrogen fertilizers are produced. These emissions are worth considering when diets and food products that use different agricultural practices are compared. An assessment of non–carbon dioxide GHG emissions in agriculture is valuable not only because of their effect on climate change but also because emissions are present even if a reduction in fossil fuel emissions occurs, eg, through efficiency improvements or from the increased use of renewable energy sources.

The relative importance of different GHGs, when all are added and weighted, depends on a range of factors (**Table 1**). An analysis of any food item must include the degree of processing, transportation mode and distances, presence of red meat, amount of nitrogen fertilizer used, manure application, and storage method. For vegetable products, energy use often is the dominant contribution of carbon dioxide emissions, but nitrous oxide emissions related to nitrogen application and fabrication also may be significant. For an analysis of vegetable products, emissions of carbon dioxide may be calculated from an energy analysis based on known amounts of carbon dioxide emissions per megajoule of energy used. Types of energy carriers should be differentiated. For example, coal emits 1.6 times more carbon dioxide per megajoule than natural gas. Emissions of nitrous oxide may be calculated if the nitrogen fertilizer or manure use during farming is known.

TABLE 1
Global Warming Potential for gases relevant to agriculture[1]

Greenhouse gases	20 y	100 y	500 y
Nitrous oxide	289	298	153
Methane	72	25	7.6

[1] Values were obtained from the Intergovernmental Panel on Climate Change (Reference 8, Table 2.14). The Global Warming Potential is an index that measures the radiative forcing of a unit mass of a given well-mixed greenhouse gas in the present-day atmosphere integrated over a chosen time horizon, relative to that of carbon dioxide.

For animal products and rice produced under flooded conditions, the calculation of GHG emissions is more complicated. For animal products, nitrous oxide emissions during manure storage and emissions of methane must be considered. During manure handling, lagoons are the main source of methane, whereas in the cultivation of rice, this gas is released when fields are under water. The methane emissions depend on the amounts of organic matter and the length of time anaerobic conditions are maintained. The decomposition of manure (urine and feces) in liquid form can produce a significant amount of methane. Higher emissions are shown when animals are kept in large numbers in confined conditions, such as dairy farms, cattle feedlots, and intensive pig farms. Under these conditions, manure usually is handled in liquid systems.

Herbivores and most ruminants are another important source of methane emissions. In these animals, cellulose and other complex carbohydrates are digested with the aid of microorganisms. The associated processes are collectively called enteric fermentation. Methane is produced in this type of microbial digestion. The amount released depends on the type of animal, the quality and quantity of feed, and the characteristics of livestock. The main ruminants that produce extensive amounts of methane are cattle, buffalo, sheep, goats, and deer, but, because of their numbers, only animals under domesticated conditions contribute significantly to climate change. The more feed intake, the higher the methane emissions. When the efficiency of converting feed into food is low, emissions per unit of food are high. Birds and pigs convert feed more efficiently than cattle and sheep. As a result, methane emissions from enteric fermentation counted per unit of beef can be the largest single contribution to total GHG emissions (discussed below).

Because methaneand nitrous oxideemitted into the atmosphere interact with other gases, eg, aerosols and radiation, a decay or enhancement of their concentration and activity is expected. Global Warming Potential (GWP) is shown in Table 1 (GWP is the relative incidence of each gas as a possible contributor to climate change). By definition, the GWP of carbon dioxide is equal to one. For example, a GWP of 25 for methane in a 100-y period means that all amounts obtained in grams of methane in the inventories should be multiplied by 25 to convert them into kg CO_2 equivalents.

On the basis of the latest expert panel report on GHG calculations for national inventories from the IPCC, we assessed non–carbon dioxide emissions for various cereals, legumes, vegetables, milk, and meats from different animals. Detailed calculations and the corresponding uncertainty analysis are reported elsewhere (13). (*See* also **Appendix A** for an example of how nitrous oxide emissions are calculated for wheat and soybeans.) For the animal products analyzed, we considered emissions during cultivation of the feed required for rearing the animals when making these estimates. As an example, the results for beef and pork are shown in **Table 2**. The roles of enteric fermentation and manure management can be observed. Poultry contributes lower non–carbon dioxide emissions than do beef and pork, with nitrous oxide emissions of 0.26-kg CO_2 equivalent/kg carcass and almost no methane emissions due to dry management of manure. No data

TABLE 2

Non–carbon dioxide emissions for producing carcasses of beef and pork

	Emissions from cattle		Emissions from pigs	
	kg CO_2 equivalents/ kg carcass	%	kg CO_2 equivalents/ kg carcass	%
Nitrous oxide				
Feed	1.25	12	0.38	13
Manure	1.07	10	0.07	3
Methane				
Manure	1.78	17	2.06	75
Enteric	6.33	61	0.24	9
Total non–carbon dioxide emissions	10.43	—	2.75	—

were available for enteric fermentation. The IPCC (8) does not report a zero value but states that not enough data on enteric fermentation of poultry are available to make a clear assessment. In this case, the percentage from feed was 93%. These examples show the diversity of variables and their relative weights influencing non–carbon dioxide GHG emissions during animal production. In addition, the comparison in meats help show the important role of enteric fermentation in total emissions.

TOTAL CONTRIBUTIONS OF GHGs TO SPECIFIC FOOD ITEMS

We also studied the total GHG emissions for 22 food items sold in Sweden and created an inventory of carbon dioxide, methane, and nitrous oxide from farm to table and used the GWPs (*see* Table 1) to estimate total emissions measured in CO_2 equivalents. Emissions of methane and nitrous oxide were obtained (explained above), and carbon dioxide emissions were calculated based on an energy analysis (3) and a subsequent calculation of carbon dioxide emissions. Allocation was based on economic principles, meaning that the allocation of resource use and emissions was based on the value of the various products obtained in a process (eg, flour and husks during milling). Losses were estimated during all stages in the food system, including preparation and consumption. The emissions for food items ready to be consumed by households in Sweden are shown in **Table 3**. Emissions during storage and handling at home also were considered. Details on calculation of carbon dioxide emissions during the production chain of soybeans are provided in **Appendix B**.

Fresh vegetables, cereals, and legumes present the lowest emissions. Meats and fruits transported by air have the highest total GHG emissions, whereas eggs, certain fish, and frozen vegetables are found in the midrange. Animal products range from 1.5 to 30 kg of GHG emissions/kg of food, with herring—a fish caught with little use of fossil fuel—and eggs at the lower end of the animal products. The values of methane and nitrous oxide emissions for beef and pork are not the same as those shown in Table 2 because of the difference in functional units: in Table 2, kilograms per carcass and in Table 3 kilograms per prepared food item. Foods that commonly have low GHG emissions, such as fruits in some circumstances, when they are transported by air, may have emissions as large as some types of meat. Fish may or may not present high emissions of carbon dioxide due to fossil fuel use. As shown in Table 3, cod emissions are close to 9 kg/kg product because of the extensive use of fuel for trawling. Cod is heavily overfished in the Baltic Sea, such that it is on the verge of extinction (14). Fuel used to catch the remaining stock is considerable but cod fishing is still profitable because of heavy subsidies for fisheries in the European Union.

To compare the values shown in Table 3 with GHG emissions resulting from activities other than eating, we considered the use of a motor vehicle. The average carbon dioxide emission per kilometer from the current passenger car fleet in the European Union is 186 g (15). The total GHG emissions shown for beef in Table 3 mean that the consumption of 1 kg domestic beef in a household represents automobile use of a distance of ≈160 km (99 miles).

PLANT AND ANIMAL PROTEIN AND THEIR CONTRIBUTIONS TO GHG EMISSIONS

Previous studies have shown that producing protein from soy and other legumes has a very low environmental effect compared with protein production from animal products (16). In this study, we also concluded that it is more "climate efficient" to produce protein from vegetable sources than from animal sources, although some animal products are fairly climate efficient. When the results shown in Table 3 are combined with the protein content per kilogram of each food item, the amount of protein available per amount of GHG emissions is distinct (**Figure 1**). Beef is the least efficient way to produce protein, less efficient than vegetables that are not recognized for their high protein content, such as green beans or carrots. The most climate-efficient way to consume protein is to eat a mixture of cereals, legumes, and fish caught in a fuel-efficient way (*see* Figure 1). Unfortunately, the fish stock is under severe threat with many stocks that are over- or fully exploited (17), leaving environmentally conscious consumers with mainly vegetarian alternatives.

EXAMPLES OF MEALS

In **Table 4**, 3 possible meals with different GHG emissions are described. For simplicity, only main ingredients are included. These 3 options for meals with similar nutritional composition represent a span in GHG emissions of a factor of 11 between the meal with the lowest and highest emission levels. The example shows how much influence food choices can have on GHG emissions.

CONCLUSIONS AND REFLECTIONS

We have studied emissions of the main GHGs in food production and consumption, namely carbon dioxide, methane, and nitrous oxide. For plant-based foods (with the exception of rice), emissions of carbon dioxide often are the dominant contribution and with nitrous oxide present in small percentages. For animal-based foods and rice, the non–carbon dioxide gases contribute significantly. Plant foods based on vegetables, cereals, and legumes present the lowest GHG emissions with the exception of those transported by airplanes. Animal products, including dairy, are associated with higher GHG emissions than plant-based products, with the highest emissions occurring in meats from ruminants. Fowl meat and eggs are fairly climate-friendly meat products.

TABLE 3

Carbon dioxide, methane, and nitrous oxide emissions from farm to table for 22 items commonly consumed in Sweden

	Emissions[1]			
Commonly consumed foods	Carbon dioxide	Nitrous oxide	Methane	Total
	kg CO_2 equivalents/kg product			
Carrots: domestic, fresh	0.38	0.04	0.0	0.42
Potatoes: cooked, domestic	0.40	0.06	0.0	0.45
Honey	0.46	0.0	0.0	0.46
Whole wheat: domestic, cooked	0.54	0.08	0.0	0.63
Apples: fresh, overseas by boat	0.80	0.02	0.0	0.82
Soybeans: cooked, overseas by boat	0.92	0.0	0.0	0.92
Milk: domestic, 4% fat	0.45	0.14	0.45	1.0
Sugar: domestic	1.04	0.03	0.0	1.1
Italian pasta: cooked	0.96	0.12	0.0	1.1
Oranges: fresh, overseas by boat	1.1	0.10	0.0	1.2
Rice: cooked	0.59	0.21	0.52	1.3
Green beans: South Europe, boiled	1.2	0.12	0.0	1.3
Herring: domestic, cooked	1.5	0.0	0.0	1.5
Vegetables: frozen, overseas by boat, boiled	2.2	0.05	0.0	2.3
Eggs: Swedish, cooked	1.7	0.74	0.04	2.5
Rapeseed oil: from Europe	1.5	1.5	0.0	3.0
Chicken: fresh, domestic, cooked	3.1	1.2	0.01	4.3
Cod: domestic, cooked	8.5	0.0	0.0	8.5
Pork: domestic, fresh, cooked	3.9	1.6	3.8	9.3
Cheese: domestic	5.0	1.3	4.5	11
Tropical fruit: fresh, overseas by plane	11	0.23	0.0	11
Beef: domestic, fresh, cooked	6.9	6.6	17	30

[1] Values represent kg CO_2 equivalents over a 100-y time period.

The analysis shows that changes toward a more plant-based diet could help substantially in mitigating emissions of GHGs. Unfortunately, this is a largely unexplored area of climate policy. Few authors have proposed changes that lower meat consumption. Smil (18) suggested that because a large percentage of beef is consumed ground in hamburgers or sausages, the inclusion of protein extenders from plant origin would be a practical way to replace red meats. McMichael et al (19) recently proposed a 10% reduction in the current global average meat consumption of 100 g per person per day as a working global target. We agree with these 2 proposals, which could be implemented simultaneously. In the long run, however, achieving

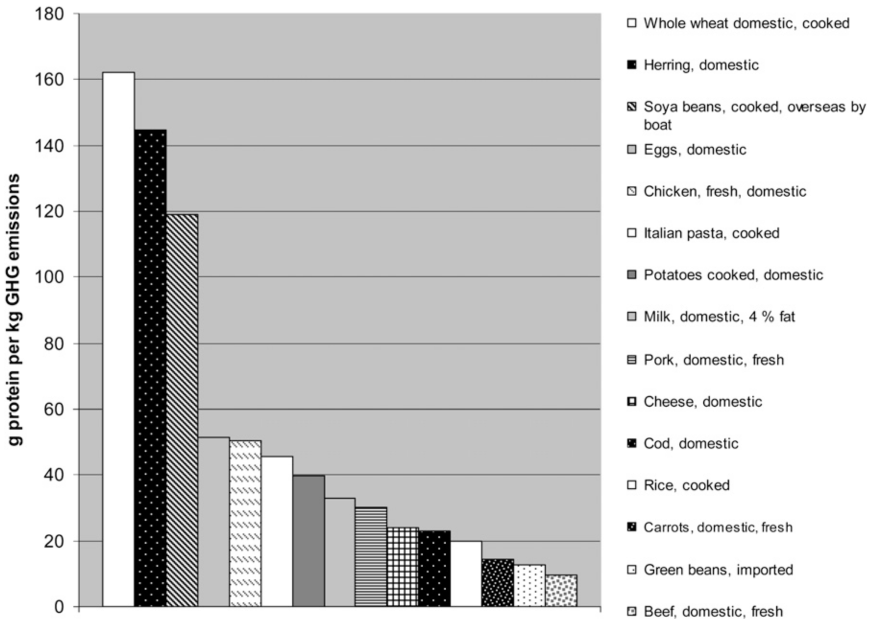

FIGURE 1. Protein content per amount of greenhouse gases (GHGs) emitted for various types of food.

TABLE 4
Main ingredients in 3 meal options from Sweden with different greenhouse gas (GHG) emissions[1]

	Edible weight	GHG emissions
	kg	*kg CO_2 equivalents*
Meal A		
Carrots: domestic, fresh, raw	0.10	0.04
Whole wheat: domestic, cooked	0.10	0.06
Soybeans: overseas by boat, cooked	0.25	0.23
Apples: domestic, fresh, raw	0.10	0.08
Total for meal A	0.55	0.42
Meal B		
Green beans: EU, boiled	0.10	0.13
Potatoes: cooked	0.30	0.14
Pork meat: cooked	0.10	0.94
Orange: overseas by boat	0.10	0.12
Total for meal B	0.60	1.3
Meal C		
Vegetables: frozen, cooked	0.10	0.23
Rice: overseas by boat, cooked	0.20	0.26
Beef: domestic, fresh, cooked	0.10	3.0
Tropical fruits: by plane, fresh, raw	0.10	1.1
Total for meal C	0.50	4.7

[1] All meals have similar nutritional compensation. Each meal has a portion of vegetables, fruits, cereal, and protein-rich food. Energy and protein content of meals is similar.

further reductions will be necessary. The magnitude of these will depend not only on the need for stabilizing levels of GHG emissions in the atmosphere but also on efficient use of arable land in a world in which the quest for renewable energy, such as biofuel, is increasing. It is not impossible to imagine a future world relying on renewable energy and in which the consumption of certain meats is an exception and reserved for certain festivities and rituals.

For the immediate future, we recommend a better synergy between environmental and health education to obtain agreement for a dietary change for the general public. Duchin (6) and McMichael et al (19) explained the health benefits that a plant-based diet would have on health and environment, and this knowledge could be translated into information campaigns. In the many actions currently proposed for climate-friendly consumption, however, more vegetarian food is hardly a main issue, if it is mentioned at all. This conclusion was made after browsing several sites offering advice for consumers and from attending many debates and seminars concerning climate change effects from food consumption. Further research is needed to understand barriers and why changes in diets have not been a main issue on the climate agenda until now. (Other articles in this supplement to the Journal include references 22–48.)

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APPENDIX A

Calculating nitrous oxide emissions during production of wheat and soybeans

The emission factor for the fraction of nitrous oxide emitted in fertilized fields depends on the amount of nitrogen applied per hectare and the crop yield. The procedure to calculate it is given by the IPCC (8). For example, conventional wheat grown in Sweden requires ≈24 kg N applied per metric tonne of crop. With an emission factor of 0.014 kg N_2O/kg N and the GWP for 100 y of age lifetime taken from Table 1, a total of between 0.10 and 0.12 kg CO_2 equivalents/kg of wheat harvest is obtained. In addition, if crop residues are left on fields, their decomposition involves nitrogen contents, and the IPCC procedure calculation leads to an additional 0.06 kg CO_2 equivalent/kg wheat harvest. Then, the total nitrous oxide from wheat is ≈1.7 kg CO_2 equivalents/kg wheat harvest. Soybeans require little fertilization. Their crop residue, however, usually is left on the field because of no-till practices. With the same procedure, an emission from fertilization gives 0.004 kg CO_2 equivalent/kg soybeans harvested but ≈0.07 from residues, given a total of nitrous oxide emissions of 0.074 CO_2 equivalent/kg soybeans harvested.

APPENDIX B

Calculating carbon dioxide emissions during production of soybeans

Irrigated soy farming in Nebraska produces ≈3.6 metric tonnes/hectare and requires an input of ≈300 L of diesel, 10 kg phosphorus fertilizers, and 26 kg potassium fertilizers. With the use of available data (20, 21), carbon dioxide emissions of 0.25 kg CO_2/kg soy harvest are obtained. Then, to obtain emissions at Swedish household consumption level, the emissions from transport, packing, storage, retailing, and cooking are added considering their corresponding losses in the food chain. For example, land and sea transport accounts for 0.32 kg CO_2/kg soy when transport overseas is included. Cooking beans at home generates ≈3 MJ/kg output, and the carbon dioxide emissions per megajoule used depends on the energy source (eg, electricity from nuclear or hydropower have much fewer emissions than coal). It is beyond the scope of this article to discuss all the details. For further examples of complete energy accounts in food analysis, *see* the report by Carlsson-Kanyama and Faist (20)