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Protein efficiency per unit energy and per unit greenhouse gas emissions: Potential contribution of diet choices to climate change mitigation

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ABSTRACT

The production, transport and processing of food products have significant environmental impacts, some of them related to climate change. This study examined the energy use and greenhouse gas emissions associated with the production and transport to a port in Sweden (wholesale point) of 84 common food items of animal and vegetable origin. Energy use and greenhouse gas (GHG) emissions for food items produced in different countries and using various means of production were compared. The results confirmed that animal-based foods are associated with higher energy use and GHG emissions than plant-based foods, with the exception of vegetables produced in heated greenhouses. Analyses of the nutritional value of the foods to assess the amount of protein delivered to the wholesale point per unit energy used or GHG emitted (protein delivery efficiency) showed that the efficiency was much higher for plant-based foods than for animal-based. Remarkably, the efficiency of delivering plant-based protein increased as the amount of protein in the food increased, while the efficiency of delivering animal-based protein decreased. These results have implications for policies encouraging diets with lower environmental impacts for a growing world population.

Introduction

Objective

The aim of the present work was to contribute to ongoing discussions about the need for dietary change by correlating the nutritional value of various foods with their potential contributions to climate change during production and transport. To achieve this aim, we compared the amounts of energy used and greenhouse gases emitted during production against the protein content of 84 common foods. This allowed us to determine the efficiency of producing and transporting protein for different food groups, namely animal products, legumes, cereals, caloric roots and squash, greenhouse-grown vegetables, field-grown vegetables and fruits. The study formed part of the ‘Household Metabolism’ project, which aims to assess the contribution to climate change of items consumed by households in Sweden, and to develop tools to allow the public to understand the impacts and take action to reduce their ecological footprint.

Background

The production, transport, processing and marketing of foods involve complex phenomena that affect not only anthropogenic-based emissions but also biological, physical and chemical interactions. The diversity of environmental impacts due to food production is probably larger than for any other human activity. Food production involves rural activities, deforestation, changes in land use, emissions into soil, water and air of biologically active and inert elements, transport of perishable substances (requiring refrigeration in the whole chain from farm to consumption and carrying risks of spreading health hazards), industrial processing, handling and storage with special requirements; and finally a high need for refrigeration and waste management at the end consumer.

Worldwide, the consumption of food contributes a substantial part of the total energy used and the total greenhouse gases (GHG) emitted. The fraction of global GHG emissions due to the agricultural sector was 32% in the year 2000 (EPA, 2006). This figure comprised 57% carbon dioxide (CO_2), 25% methane (CH_4) and 19% nitrous oxide (N_2O), showing that not only are non-CO_2 gases relevant in food consumption, but energy use leading to CO_2 emissions is also important. So far, the large contribution of food consumption to climate change impacts has been blurred by the fact that emissions of non-CO_2 gases from agriculture (CH_4, N_2O and

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refrigerants) are those usually stressed in assessments of the sector. However, the inefficiencies in livestock production reported by a number of authors also lead to large contributions of CO_2. Furthermore, a recent report showed that if induced land use change is included in the analysis, the food system may be responsible for 30% of all greenhouse gas emissions in the UK (Audsley et al., 2009). The same study found that livestock can contribute 75% of all induced land use change for food production. Other authors have estimated that 18% of global GHG emissions are due to livestock consumption (Steinfeld et al., 2006).

Environmental impacts not directly related to climate change, such as water use and eutrophication (Steinfeld et al., 2006) or deforestation and desertification (Asner et al., 2004), can also be relevant impacts from livestock production. In some areas, livestock rearing can be of benefit due to soil type or geographical or climatic conditions, and can even contribute to carbon capture. In these cases, however, the stocking density (number of animals per hectare) to achieve environmental benefits is far lower than required for present consumption. For example, a stocking density of around 0.12–0.17 animals per ha for cattle in Central Argentina seems to be the limit to avoid detrimental effects from overgrazing (Andrioli et al., 2010). The same applies to livestock rearing in poor areas – if the density is low, production can be both sustainable and beneficial.

A change to a diet based more on foods of plant origin has been suggested by different authors as a way to reduce environmental impacts and mitigate the influence of food production on climate change (Carlsson-Kanyama, 1998; Carlsson-Kanyama et al., 2003; Duchin, 2005; Stehfest et al., 2009; Garnett, 2009; Carlsson-Kanyama and González, 2009). Besides benefiting the environment, reducing animal-based products in the diet could also improve public health by preventing a number of chronic degenerative diseases (WHO–FAO, 2003; McMichael et al., 2007; Friel et al., 2009; WCRF, 2009).

Methods

Life cycle inventories of energy and GHG

Previous results from life cycle inventories for production and transport of foods were reviewed and we also performed new calculations of the energy used and GHG emitted for the foods analysed. Primary agriculture and processing input data and yields were obtained from statistics for each country (Carlsson-Kanyama and Faist, 2001; Carlsson-Kanyama et al., 2003). Data on energy and emissions of different fuels for machinery and transport were taken from IPCC (2006). Fertiliser manufacturing uses large amounts of energy and produces direct emissions of N_2O. We used emissions data for fertiliser manufacturing from Kramer et al. (1999). Furthermore, N_2O emissions occur when N is applied to soil in the form of artificial fertiliser, manure and plant residues. Data for such soil emissions were obtained from Carlsson-Kanyama and González (2007), who also give a summary of uncertainties in emissions of non-CO_2 GHGs from food production. Electricity used in processing has different origins for different regions. Data from IEA (2009) for local conditions in different countries were used, combined with primary data from IPCC (2006) to obtain energy and emissions per unit electricity consumed in each country involved. Transport distances were determined using the programme GoogleEarth (http://www.google.com), and specific energy and emissions for refrigerated and non-refrigerated transport were taken from Carlsson-Kanyama and Faist (2001). Port operations and handling logistics were not included in the analysis.

A total of 84 individual food items were analysed. In some cases, a number of different production techniques and countries of origin resulted in a range of data for one particular item, which enabled us to assess part of the uncertainty corresponding to the various options in international trade. For example, as it will be shown below, eight cases for beef obtained from different origins were analysed: United Kingdom, Sweden organic, Sweden conventional, Argentina, Uruguay, Brazil, France and Ireland. The results for these eight items cannot be compared to assess better or worse means of production and handling, because they represent a diversity of techniques and conditions such as grazing of natural or cultivated grassland, using local crops or producing livestock with imported feeds. However, the variation in the data can provide a realistic average of the impacts of food consumption on global trade.

The functional unit used was 1 kg of food product delivered to the entry port of Gothenburg. For meats the functional unit was bone-free carcass, i.e., large pieces of meat without main bones cut from hanging warm carcasses. A factor of 0.7 was assumed for bone-free carcass with respect to carcass for all meats (Cederberg et al., 2009). For cereals and beans the functional unit used was 1 kg of dry grain at the port, while for fruits and vegetables wholesale packaging was not included as the products were assumed to be shipped in large crates.

Transport energy and emissions were considered on a per kg basis so that with the distinction of refrigeration, they affected all foods equally. Refrigeration was taken into account for all animal products and for certain vegetables and fruits, and gave an additional 20% of energy and emissions for transportation on a per kg basis (Carlsson-Kanyama and Faist, 2001; Tassou et al., 2009).

Protein in terms of energy and GHGs

A per-kg analysis done in the life cycle inventories does not represent a proper account of energy and emissions of actual human nutrition needs. Thus, the nutritional contents of foods which satisfy the human diet should be introduced. Here, we concentrate our study in protein, which is one of the essential contributors to good nutrition. Using a complete free-access food composition database provided by the United States Department of Agriculture (USDA, 2009), we determined the protein content per kg of the food products. Then, we could correlate this with the energy use and GHG emissions obtained in the life cycle inventories.

We defined two magnitudes that resemble efficiencies:

- the amount of protein delivered to the wholesale point of Gothenburg port per unit energy spent,
- the amount of protein delivered to the wholesale point of Gothenburg per unit GHG emitted.

These magnitudes are called here protein delivery efficiencies, in terms of energy and of GHG, respectively, and comprise the total process of production from cradle to gate and the transportation to the common wholesale point.

Results

Energy and emissions for common foods

Table 1 summarises the energy and emissions derived from the production and transport of 1 kg of food items to the port of Gothenburg, Sweden. Data obtained in the present work are marked Household Metabolism (HM); otherwise the source is listed in Table 1.

The data for beef are quite interesting, depicting a diversity of origins and production techniques. Cattle on pastures consistently require less energy than those in feedlots, but emissions are also consistently higher. The results for Uruguay and Brazil correspond

Table 1
Energy use and GHG emissions in the production of 1 kg of food transported to the entry port of Gothenburg, Sweden.

Food type	Country of origin	Energy used (MJ/kg)	GHGs (kg CO_2 eq./kg food)	Source
Beef (1 kg bone-free carcass)	United Kingdom[b]	40	23	(Williams et al., 2006)
	Sweden[c]	37	32	(Cederberg and Stadig, 2003)
	Sweden[b,d]	82	20	HM[a]
	France[e]	70	39	(Veysset et al., 2010)
	Argentina[f]	52	22	HM[a]
	Uruguay[g]	38	29	HM[a]
	Brazil[g]	9.0	40	(Cederberg et al., 2009)
	Ireland		29	(Casey and Holden, 2006)
Mutton & lamb (1 kg bone-free carcass)	United Kingdom[b]	33	24	(Williams et al., 2006)
	Sweden[b,d]	65	17	HM[a]
	Uruguay[g]	40	36	HM[a]
Pork (1 kg bone-free carcass)	United Kingdom[b]	25	9.2	(Williams et al., 2006)
	Sweden[b,d]	31	7.2	HM[a]
Chicken (1 kg bone-free carcass)	United Kingdom	18	6.6	(Williams et al., 2006)
	Sweden	29	2.9	HM[a]
	Norway	33		(Ellingsen and Aanondsen, 2006)
Fish (1 kg carcass)[h]	Farmed salmon, Canada	46	3.6	(Pelletier et al., 2009)
	Farmed salmon, Chile	51	3.6	(Pelletier et al., 2009)
	Farmed salmon, Norway	38	2.6	(Pelletier et al., 2009)
	Tuna, fished, Spain	26	2.6	(Hospido and Tyedmers, 2005)
Eggs (1 kg egg)	United Kingdom	14	5.5	(Williams et al., 2006)
	Sweden, local feed[i]	12	1.6	HM[a]
	Sweden, imported feed[d]	17	1.9	HM[a]
Dairy (1 kg product)	Milk, United Kingdom	3.0	1.1	(Williams et al., 2006)
	Milk, Sweden[c]	3.1	1	(Cederberg and Stadig, 2003)
	Cheese, Sweden	38	8.8	(Berlin, 2002)
Legumes (1 kg dry beans)	Soybean, Brazil	4.0	0.38	HM[a]
	Soybean, Argentina or Brazil or USA	3.4	1.3	(Williams et al., 2006)
	Soybean, USA[j]	6.8	0.46	Energy: (Pimentel, 2009); GHG: HM[a]
	Beans, United Kingdom	2.9	1.0	(Williams et al., 2006)
	Brown beans, Sweden	7.4	0.68	HM[a]
	Faba beans, Switzerland[k]	4.6	0.94	(Köpke and Nemecek, 2010)
	Peas, Sweden	3.5	0.49	HM[a]
Cereals (1 kg dry grain)	Wheat, Sweden	2.0	0.38	HM[a]
	Wheat, United Kingdom	2.9	0.83	(Williams et al., 2006)
	Wheat, USA[j]	8.9	0.80	Energy: (Pimentel, 2009); GHG: HM[a]
	Wheat, United Kingdom	1.7	0.29	(Brentrup et al., 2004)
	Barley, United Kingdom	2.8	0.76	(Williams et al., 2006)
	Barley, Sweden	2.6	0.43	HM[a]
	Rye, Sweden	2.1	0.36	HM[a]
	Oats, Sweden	2.9	0.47	HM[a]
	Maize, USA	6.1	0.73	HM[a]
	Maize, USA	6.0	0.58	Energy: (Pimentel, 2009); GHG: HM[a]
	Maize, USA	2.4	0.68	(Williams et al., 2006)
	Rice, USA	6.6	1.1	HM[a]
	Rice, USA[j]	9.6	1.3	Energy: (Pimentel, 2009); GHG: HM[a]
	Rice, Japan	7.4	1.2	HM[a]
Tubers, roots & squash (1 kg product)	Potatoes, Sweden	1.5	0.16	HM[a]
	Potatoes, Switzerland	1.5	0.14	HM[a]
	Potatoes, Denmark	0.8	0.09	HM[a]
	Potatoes, United Kingdom	1.8	0.27	(Williams et al., 2006)
	Potatoes, USA[j]	4.3	0.35	Energy: (Pimentel, 2009); GHG: HM[a]
	Beetroot, Sweden	1.1	0.11	HM[a]
	Squash, Sweden	0.96	0.09	HM[a]
Horticulture in heated greenhouses (1 kg product)	Tomatoes, Sweden, electricity and propane heating	51	3.7	HM[a]
	Tomatoes, Holland, natural gas heating	49	2.8	HM[a]
	Tomatoes, United Kingdom, natural gas heating	130	9.4	(Williams et al., 2006)
	Cucumbers, Sweden, electricity heating	41	0.75	HM[a]
	Cucumbers, Sweden, fuel oil heating	35	2.6	HM[a]
	Sweet peppers, Sweden, fuel oil heating	133	10	HM[a]
Horticulture in open field (1 kg product)	Tomatoes, Spain	3.0	0.37	HM[a]
	Tomatoes, USA[j]	3.7	0.28	Energy: (Pimentel, 2009); GHG: HM[a]
	Cucumbers, Sweden	0.84	0.08	HM[a]
	Cabbage, Sweden	1.1	0.12	HM[a]
	Broccoli, Sweden	3.6	0.37	HM[a]
	Carrots, Sweden	0.97	0.09	HM[a]
	Carrots, Switzerland	1.7	0.14	HM[a]
	Lettuce, Sweden	1.4	0.13	HM[a]

Table 1 (*continued*)

Food type	Country of origin	Energy used (MJ/kg)	GHGs (kg CO_2 eq./kg food)	Source
	Lettuce, Holland	1,3	0.14	HM[a]
	Lettuce, USA	3.9	0.32	HM[a]
	Onions, Sweden	1.0	0.10	HM[a]
Fruits (1 kg product)	Apples, Sweden	0.63	0.06	HM[a]
	Apples, New Zealand	6.1	0.48	HM[a]
	Apples, New Zealand	6.3	0.50	(Milà i Canals et al., 2007)
	Apples, France	1.6	0.12	HM[a]
	Apples, European Union	2.3		(Milà i Canals et al., 2007)
	Apples, Switzerland	2.2	0.16	(Mouron et al., 2006)
	Apples, USA[j]	5.8	0.38	Energy: (Pimentel, 2009); GHG: HM[a]
	Oranges, USA	3.7	0.33	HM[a]
	Oranges, USA[j]	3.8	0.32	Energy: (Pimentel, 2009); GHG: HM[a]
	Cherries, Sweden	3.0	0.26	HM[a]
	Cherries, USA	5.0	0.45	HM[a]
	Strawberries, Sweden	2.8	0.21	HM[a]
	Strawberries, USA	5.4	0.55	HM[a]

[a] Household Metabolism (HM) indicates values calculated in the present work using primary input data. Land and port logistics not included.
[b] Feedlot.
[c] Organic.
[d] Conventional, feed imported from overseas.
[e] Average of the range of values given in the source.
[f] 80% Pasture and 20% feedlot.
[g] 100% Pasture.
[h] Carcass assumed as 70% of landed weight.
[i] Feed produced in Sweden.
[j] Includes energy for human labour.
[k] Dry matter data corrected by 11% water content.

to 100% pasture-fed beef, although in Uruguay the pasture was considered to be sown and fertilised while in Brazil it was natural and input-free. Due to this management difference, the energy required to produce beef in Brazil is very low (Cederberg et al., 2009). The nutritional value and digestibility of grass are lower than those of feedlot feed or cultivated grass leys, which e.g., in Uruguay usually contain alfalfa and clover. Cattle on grass-only pastures need more time to reach slaughter weight and emissions are thus higher than for cultivated leys, which in turn produce higher emissions than feedlots. For Argentina we considered 80% cultivated grassland and 20% feedlot feed, and therefore the results show intermediate energy and GHG emissions value per kg beef. Our results for beef production in Sweden show the highest energy used (82 MJ/kg). This is a consequence of considering mostly imported ingredients from overseas in feedlot feeds. For eggs produced in Sweden we analysed both cases, imported feed and local feed, and found the energy use for the imported feed to be 35% higher and the GHG emissions 20% higher (Table 1).

Transportation influenced the various food groups differently, depending on the magnitude of energy and emissions derived from production. For instance, transporting 1 kg beef from Argentina to Gothenburg took around 7% of the total energy used and 1.3% of the total emissions. In contrast, transporting grain or beans from Brazil or Argentina to Sweden can represent as much as 60% of the total energy and emissions involved. Due to transport, feed requirements can led to substantial emissions of CO_2 in animal production, in cases surpassing the contribution of non-CO_2 GHGs. Transport has been extensively studied by other authors, e.g., a study on imported apples into UK showed that transport and storage made a large contribution to total energy and emissions (Milà i Canals et al., 2007).

The comparison in Table 1 is on a per kg basis, which may be misleading regarding the actual nutritional value of foods. We therefore studied a key nutritional component, protein, to complement the comparison of animal and plant foods.

Protein delivery efficiencies

The content of protein in the foods analysed, as well as energy, emissions, and protein delivery efficiencies are depicted in Table 2. For food types where several figures on energy use and GHG emissions were available, we took the average of all figures. For instance, the energy use and GHG emissions for beef in Table 2 are the average of the seven values for energy and eight values for GHGs given in Table 1. These average values (47 MJ and 29 kg CO_2 eq. per kg of bone-free beef) were then used to assess the protein delivery efficiencies.

The protein delivery efficiency in terms of energy use for animal products ranged from 4 to 11 g protein per MJ of energy invested, while that for cereals ranged from 8 to 57 g protein/MJ and for legumes from 41 to 77 g protein/MJ (Table 2). The energy use efficiency to deliver protein from plant sources was thus much larger than for animal-based foods.

Fig. 1 shows the range of values obtained for protein delivery efficiency in terms of energy use for the products listed in Table 2. Legumes had the highest efficiency, closely followed by cereals. Livestock products had values as low as most horticultural vegetables and had 4- to 8-fold lower efficiency than legumes and cereals (except rice). Separate linear interpolations for plant- and animal-based foods were both statistically significant. In Fig. 1, the correlation coefficients (Navidi, 2006) are shown ($r = 0.94$ for plant-based and $r = -0.78$ for animal-based), demonstrating the correlation between protein delivery efficiency in terms of energy and protein content (Fig. 1).

The protein delivery efficiency in terms of energy for plant-based foods showed a surprising trend: the higher the protein content in the food, the higher the efficiency. This feature should be confirmed with further studies in which more products are analysed. However, the present results appear very solid for plant foods, since we were able to gather a set of data that covered the whole protein content range. For animal products the reverse

Table 2
Protein content in selected foods, energy use, GHG emissions, and the protein delivery efficiency of these foods in terms of energy use and GHG emissions.

		Protein content of food[a] (g protein/kg)	Energy use[b] (MJ/kg)	GHG emissions[b] (kg CO_2 eq./kg)	Protein delivery efficiency energy (g protein/ MJ)	Protein delivery efficiency GHG (g protein/kg CO_2 eq.)
Meats	Beef	206	47	29	4.4	7.1
	Mutton and lamb	193	46	26	4.2	7.6
	Pork	206	28	8.2	7.3	25
	Chicken	188	27	4.7	7.0	39
	Fish	207	40	3.1	5.1	67
Dairy and eggs	Egg	126	14	3.0	9	42
	Milk	32	3.0	1.0	11	31
	Cheese	249	38	8.8	6.5	28
Legumes	Bean[c]	210	5.1	0.86	41	246
	Pea	245	3.5	0.49	70	495
	Soybean	365	4.8	0.72	77	505
	Faba bean	261	4.6	0.94	57	277
Cereals	Wheat	111	3.9	0.58	29	192
	Maize	94	4.8	0.67	19	141
	Oats	169	3.0	0.47	57	359
	Barley	111	2.7	0.60	41	187
	Rye	103	2.1	0.36	48	283
	Rice	66	7.9	1.2	8.4	56
Vegs	Potatoes	17	1.8	0.19	9.4	89
	Beetroot	16	1.1	0.11	15	146
	Squash	10	1.0	0.09	10	106
	Tomato	9	3.4	0.30	2.6	27
	Tomato GH[d]	9	77	5.3	0.1	1.7
	Cucumber	7	0.8	0.08	7.7	84
	Cucumber GH[d]	7	38	1.7	0.2	3.9
	Carrot	9	1.4	0.12	6.9	81
	Onion	11	1.0	0.10	10	116
	Lettuce	12	2.2	0.20	5.4	61
	Broccoli	28	3.6	0.37	7.7	75
Fruits	Apple	3	3.6	0.28	0.7	9.2
	Orange	7	3.8	0.32	1.9	22
	Cherry	11	4.0	0.35	2.7	31
	Strawberry	7	4.1	0.38	1.6	18

[a] Nutrition data from USDA (2009).
[b] Average of values given in Table 1 for each food product.
[c] Average of brown and field beans.
[d] Produced in heated greenhouses.

was observed: the higher the protein content, the lower the protein delivery efficiency in terms of energy (negative slope in Fig. 1).

We then determined the protein delivery efficiency with respect to GHG emissions, i.e., the protein obtained per kg of GHG emitted in the production and transport of the food up to the wholesale point of the Gothenburg port. The results shown in the right-hand column of Table 2 were plotted with interpolations for plant and animal products as before (Fig. 2). For plant-based protein, a similar trend as for protein delivery efficiency in terms of energy use was observed for GHG emissions.

For plant foods, linear interpolation revealed a correlation between the efficiency of protein delivery per kg of GHG emitted and the protein content of the products analysed ($r = 0.91$). Similarly to the delivery efficiency in terms of energy use, the GHG efficiency of obtaining protein from plant-based foods increased as the protein content increased. Data for animal foods plotted also in Fig. 2 do not show correlation ($r = -0.08$). In this case non-CO_2 GHG gases have different weights on emissions for each animal product. We will explain it in the discussion section.

Plotting energy efficiency vs. GHG efficiency for protein delivery revealed a strong correlation between the two for plant-based foods ($r = 0.97$) (Fig. 3). The result was not obvious a priori due to the weighting of different processes and specific determination of the protein content of foods.

Note that both axes in Fig. 3 include grams of protein (per unit energy or GHG emissions), so the gradient in the linear interpolation for plant foods has units kg CO_2 eq./MJ, which is an interesting parameter representing the GHG emission density per MJ energy used. The gradient obtained for plant foods was 0.16 kg CO_2 eq./MJ and represents the average emission density for plant foods. These results include production stages, fertiliser manufacturing, processing and transport up to the wholesale point.

For animal-based foods, the efficiency of protein delivery per unit energy shows weak correlation with that for GHG emissions ($r = 0.26$, Fig. 3). Again, this may be attributed to the large contribution of non-CO_2 GHGs from livestock and different relative contributions of these from different animal-based foods, which are explained in the next section.

Discussion

In agreement with previous works by different authors, Table 1 shows lower energy use and emissions for plant-based foods, with the exception of greenhouse-grown vegetables. It has also been reported that air-freighted vegetables give high emissions (Carlsson-Kanyama and González, 2009). With the exception of the specific cases of heated greenhouses and air freight in this study, the differ-

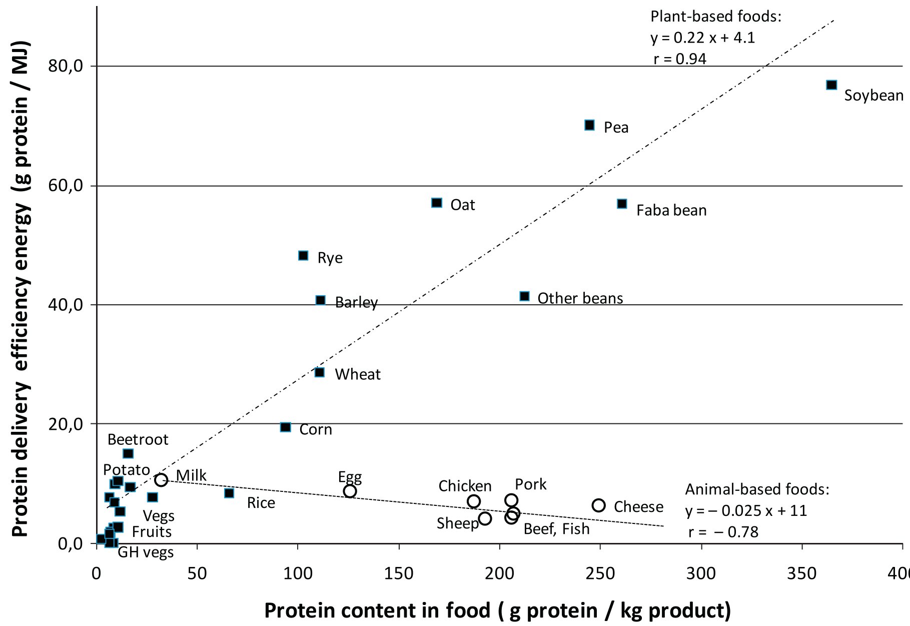

Fig. 1. Protein delivery efficiency in terms of energy use as a function of food protein content (squares: plant-based foods; circles: animal-based). The correlation coefficient *r* is shown in linear interpolations.

ences between animal and plant products are generally much larger than the differences arising from transport or country of origin. This has led to claims that a change in diet to include more plant foods would be the most effective way to reduce potential climate change contributors.

In Fig. 1, the striking difference on protein delivery efficiency between animal- and plant-based foods may be related to the nature of livestock production, particularly feed conversion. Since energy is more related to CO_2 emissions than to non-CO_2 emissions, these results show that emissions related to CO_2 in food production are significant. For plant-based foods the protein delivery efficiency increases as the protein content increases (positive correlation), while for animal-based products a decrease of efficiency is obtained as protein content increases (negative correlation). However, for a conclusive assessment of this decrease in efficiency in animal foods more data are needed, with details for specific meats and dairy products representing a larger diversity of protein contents. To our knowledge, such data are currently unavailable. It can be inferred from Fig. 1 that the slope could change to a constant level at most, but it would be very unlikely to rise as was observed for plant foods.

Large protein delivery efficiencies in terms of energy for legumes and cereals in Fig. 1 could partly explain why modern agriculture is able to feed such large numbers of livestock with the energy resources available, despite the low feed conversion efficiency of livestock and the long transport distances for feed ingredients. The basic feed concentrate ingredients (soybeans, peas, barley, oats, maize, other legumes and cereals) have high protein delivery efficiency in terms of energy use that increases as the protein content increases. This particular property enables protein in high concentration to be fed to livestock with minimum energy use.

Legumes and cereals, with the exception of rice, were also the most efficient sources of protein delivery in terms of GHGs. Animal products had relatively lower GHG efficiency (Fig. 2) than energy efficiency (Fig. 1). This was due to the larger contribution of non-CO_2 gases, mainly N_2O and CH_4, in livestock production. In agreement with previous works, ruminants showed the lowest protein delivery efficiency in terms of GHG as a consequence of higher CH_4 emissions. For example, a meal based on beef is associated with 8-fold higher GHG emissions than a meal based on legumes and grains and 3-fold higher GHG emissions than a meal based on pork (Carlsson-Kanyama, 1998; Carlsson-Kanyama and González, 2009).

The quality of the protein is also important. It is beyond the scope of the present study to discuss this matter in detail, but the World Health Organization and the Food and Agricultural Organization, and diverse nutrition research, have provided data showing the adequacy of vegetable protein when cereals and legumes are combined (WHO–FAO, 2003; Harvard, 2010). Due to the very low energy required by certain vegetables, the protein delivery efficiency of some foods that are clearly not protein-rich (e.g., potato or squash) can be higher than that of protein-rich animal products.

For animal foods there was an interesting difference between efficiencies in terms of energy or GHGs: there was no correlation between the GHG efficiency and the protein content in foods ($r = -0.08$). This might be due to the large contribution of non-CO_2 gases to total emissions from livestock not uniformly affecting the various animal foods analysed. For instance, CH_4 emissions represented a large percentage in beef and milk production, but were almost negligible for poultry and eggs. In a previous study, we reported non-CO_2 emissions for different livestock products and estimated the associated uncertainties (Carlsson-Kanyama and González, 2007).

Fig. 3 depicts an interesting property for plant-based foods: both protein delivery efficiencies, in terms of energy or GHGs, correlates. It means that a plant food that provides protein with a relatively low impact in terms of energy use will also have a low impact in terms of GHG emissions. An immediate consequence of this correlation between the two types of efficiency is that either can be used to assess the relative contribution of particular foods. For animal-based foods in Fig. 3, note that a narrow range in energy terms (vertical axis) corresponds to a wide range in GHG emissions (horizontal axis). This shows again, as in Fig. 2, the effect of very different contributions of non-CO_2 GHGs on each livestock product.

A number of previous studies have identified a change in diet as a means to mitigate climate change and other environmental footprints of food consumption (Carlsson-Kanyama, 1998; Duchin,

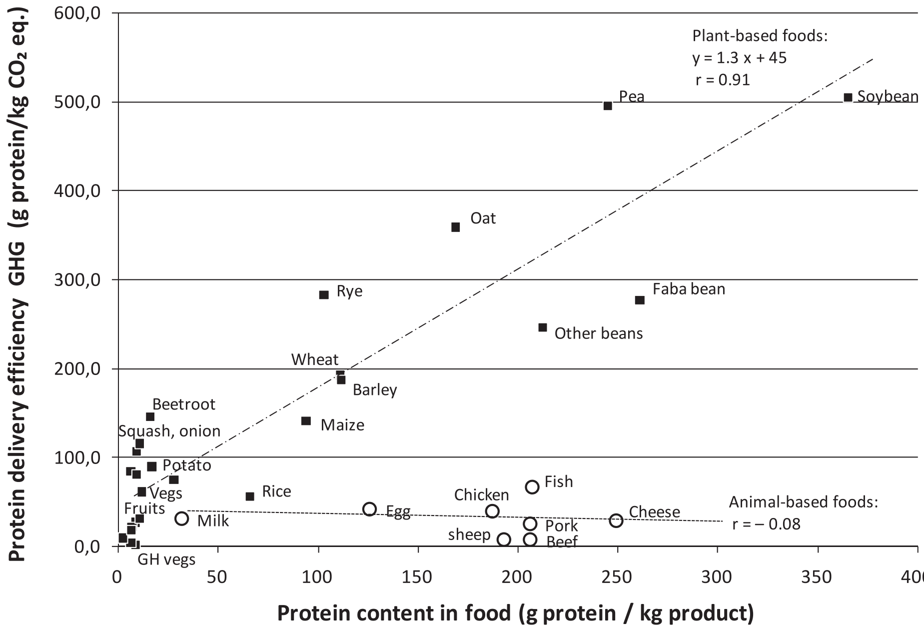

Fig. 2. Protein delivery efficiency in terms of GHG emission as a function of food protein content (squares: plant-based foods; circles: animal-based). The correlation coefficient *r* is shown in linear interpolations.

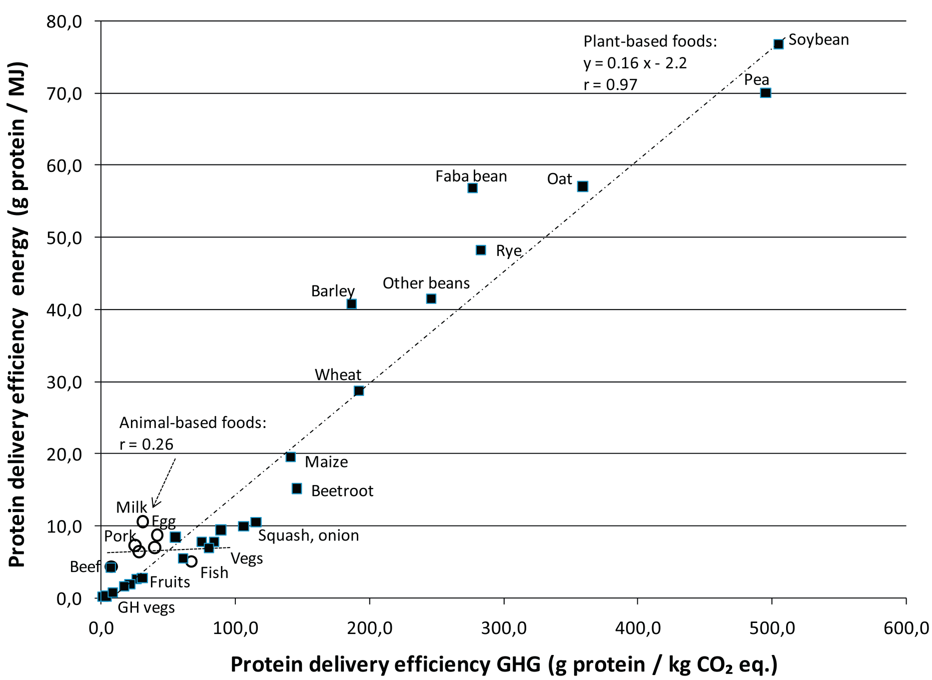

Fig. 3. Correlation between protein delivery efficiencies for energy and GHG emission (squares: plant-based foods; circles: animal-based). The correlation coefficient *r* is shown in linear interpolations.

2005; Steinfeld et al., 2006; McMichael et al., 2007; Garnett, 2009; Carlsson-Kanyama and González, 2009; Friel et al., 2009; Stehfest et al., 2009). The recommendations mostly involve reducing meat consumption. It is noteworthy that even back in the 1970s, some authors were pointing out the benefits of a more vegetarian diet for resource efficiency (e.g., Lappé, 1971; Pimentel and Pimentel, 1979). However, such recommendations have been largely ignored over the intervening decades and global meat consumption has continued to increase (McAlpine et al., 2009).

Arguments against a reduction in meat consumption or in consumption of other animal products commonly cite the valuable nutrients provided by meat products. The main nutrients known to be easily obtained from animal products are protein, iron and vitamin B12, protein being the focus in the present study. However, while these nutrients are readily available in animal products, plant-based protein has been shown to provide all the essential amino acids needed to sustain human health (Harvard, 2010). Iron is also abundant in plant-based foods, especially in green leaves, legumes and whole grains. The bioavailability may not be as high as for red meat, for instance, but in a diverse plant-based diet iron has shown to be of no concern. The amount of vitamin B12 needed to sustain human health is very small and might be well covered by the intake of small amounts of animal products or supplements. Furthermore, it appears that high consumption of meat and dairy products in the Western diet has created wide scale nutritional problems rather than solving them (WHO–FAO, 2003; WCRF, 2009; Harvard, 2010).

Industrially prepared meals are becoming more common at the expense of home-cooked foods in many societies, including Sweden, where expenditure on meals in restaurants has increased over a number of years (SCB, 2010). The food processing industry has developed a variety of products to provide convenience foods for each meal of the day. So far, however, this development has not included extensive use of protein from plant-based ingredients, which are also suitable for food processing into rich, concentrated convenience foods. For example, legumes, cereals and nuts can provide a large diversity of spreads and beverages for similar purposes as dairy products. The range of alternative foods usually sold through health food shops (e.g., soy products such as tofu, tempeh, bean burgers, and even ready-to-eat meals based on grains, legumes, vegetables and oils) demonstrates that the processing and marketing of plant-based convenience foods can be as successful as for meals based on animal products. However, these alternatives have not been reported as a possible solution to environmental issues and consumer convenience. Furthermore, the demand for such foods is not yet high enough to generate a reduction in the global climate burden.

The growing concentration of population in urban areas demands nutritionally dense foods that are also convenient to handle and consume. Animal-based products have shown public acceptance and were largely developed in standardised ways. Though, plant-based foods can present advantages in storage, safety, and waste management against animal-based. On the other hand, obesity is a growing problem for the increasingly sedentary urban population, even in developing countries (Popkin, 2001), so providing less energy dense foods of vegetarian origin could avert both the obesity epidemic and the climate change problem (Michaelowa and Dransfeld, 2008).

It could also be rightly argued that cultural customs motivate people to consume large amounts of animal products (see for instance Smil, 2002). Nevertheless, in cases of need or shortage, people have adapted and created new cultural customs that suit environmental conditions, e.g., the development over millennia of soy products in East Asia, vegetarianism in India and various cereal and bean-based diets found in African and Latin-American cultures. On the other hand, some meat-loving cultures have been promoted by convenient conditions and trade. For instance, since the end of the 19th century Argentina has been a large beef producer, and domestic consumption is also high. In recent years the Argentinean government has intervened to keep beef prices low, resulting in an increase in beef consumption per capita from the already high 62 kg in 2003 to 73 kg in 2008. Restrictions on exports and subsidies in the form of feed bonuses for feedlots since 2006 are probably also behind the latest increase in domestic beef consumption in Argentina.

An increasing number of environmental consequences, not only those related to climate change, have been attributed to animal production and consumption in different studies. Environmental limitations appear to inevitably demand more efficient food consumption, which is readily achievable by lowering meat consumption. Research in recent decades has provided mounting evidence of the benefits of reducing livestock production and meat consumption. Note that the proposals do not suggest complete elimination of animal products but rather a partial change to other food groups. The focus in the developed countries has long been on animal-based foods where this is energetically and economically possible, and the developing countries are now also moving in this direction. Livestock production can be convenient in some areas (Garnett, 2009), and small amounts of animal products can be beneficial for improving health in certain populations (McMichael et al., 2007). However, protein deficiency is generally due to lack of variety and quantity of food rather than to lack of meat. Solving global malnutrition or famine with animal-based foods would create a new array of problems arising from the high environmental impacts of these foods, whereas a diverse and well designed plant-based diet could provide protein at the lowest possible environmental cost. National and international policy should therefore shift its focus to plant-based products.

Innovative foods based on plant ingredients could also be encouraged to replace similar meat-based products. For instance, cereals, legumes and oilseeds can be the basis for spreads and fillings that can easily replace dairy or cold meats in sandwiches. Fast foods present a great opportunity for including plant-based replacements of livestock products. There are already examples of vegetable proteins used as extenders in meat products, and some studies have demonstrated the benefits of increasing the percentage of such products (Smil, 2002). The concept could be applied widely for different foods, and policies should encourage these initiatives. In some cases, research funding and possibly subsidies will be needed to stimulate production and marketing in certain areas. However, with the outstanding communication and education techniques available nowadays, the acceptance of new food products could be much faster and easier than in the past.

The discussion above indicates that it would be useful to have a huge open database so that the emissions density and nutrient delivery efficiency for a variety of food groups and countries could be readily determined. The results could benefit further studies on e.g., the environmental relevance of choices of foods or country of origin. An interesting initiative in this regard is the ongoing work on establishing a standard for calculating carbon footprints for products (ISO, 2010). However, some fast food restaurants are already presenting the carbon footprint of food items sold (such as the Max hamburger chain: http://www.max.se/en/).

Conclusions

Protein is a limiting nutrient that is essential for good nutrition and protein deficiency is known to cause a variety of health problems. This study examined the energy use and GHG emissions involved in producing and transporting protein in foods (locally produced and imported) to a wholesale point in Gothenburg, Sweden. Life cycle inventories from previous works were reviewed and new calculations were made for food groups including meats, legumes, cereals, field-grown vegetables, greenhouse-grown vegetables and fruit. Using data on the protein content of these foods we assessed the energy use and GHG emissions efficiency of delivering protein, i.e., the number of grams of protein delivered to the wholesale point per unit energy used and per unit GHG emitted in production and transport.

Whether in terms of energy spent or emissions of GHGs, this study showed that the efficiency of delivering protein to an entry port in Sweden was much higher for plant-based foods than for animal-based. In addition, plant-based protein had the specific attribute of increasing efficiency with increasing protein content of the food. Therefore, strategies aimed at feeding a growing world population and reducing contributions to climate change should include measures to encourage a more vegetarian diet with the focus on consuming vegetable products with high protein content, such as legumes, nuts and grains. These results could encourage industry and entrepreneurs to produce an attractive variety of convenience foods with a low environmental impact.

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