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Nutrient density as a metric for comparing greenhouse gas emissions from food production

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Abstract Dietary Guidelines for many countries recommend that people should eat 'nutrient dense' foods, which are foods with a high nutrient to energy ratio; and that people should limit their intake of saturated fat, added salt or added sugar. In addition, consumers and environmentalists increasingly want their food to be produced with a low impact on the environment, including reduced greenhouse gas emissions (GHGE), yet agriculture is a major source of CH_4 and N_2O emissions, as well as producing CO_2 emissions. Current research on GHGE from agriculture does not incorporate the nutritional value of the foods studied. However, the nutritional content of food is important, given the prevalence of malnutrition, including obesity (due to over-consumption of foods high in energy yet low nutritional density), and the negative health impacts they produce. This paper introduces the metric, emissions/unit nutrient density,

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and compares the results with three other metrics: emissions intensity (t CO_2e/t product), emissions/t protein and emissions/GJ. The food products examined are wheat flour, milk, canola oil, lean lamb, lean beef, untrimmed lamb and untrimmed beef. The metric t CO_2e/unit nutrient density was the preferred metric to use when examining GHGE from food production because it compares different types of products based on their nutritional value, rather than according to singular nutrients such as protein, or specific attributes such as product weight or energy content. Emissions/unit nutrient density has the potential to inform consumer choices regarding foods that have a higher nutritional content relative to the GHGE generated. Further analysis would be useful to develop and expand the use of this metric further.

Abbreviations

CO_2e	Carbon dioxide equivalents
GHGE	Greenhouse gas emissions
MFP	Milk fat plus protein
RDA	Recommended dietary allowance

1 Introduction

Health experts have long advocated a ‘balanced’ diet; one that is mainly based on a variety of whole foods in order to improve health by preventing micronutrient deficiencies and reduce the risk of chronic diseases (NHMRC 2013). In comparison to the traditional hunter-gatherer diet, which is predominantly plant-based supplemented with lean animal protein, the current western diet is significantly higher in energy density due to higher content of refined fats and carbohydrates, yet lower in nutritional content, contributing the global rise in obesity and related chronic health conditions (Drewnowski 2005; Martin et al. 2013). Consequently, dietary guidelines for Australia and America (NHMRC 2013; US DEPT HHS 2005) recommend that people eat ‘nutrient dense’ foods, which are foods with a high nutrient to energy ratio, and that people should limit their intake of saturated fat and added sugar.

Consumers and environmentalists additionally want their foods to be produced humanely and with a low impact on the environment. The environmental impact of the current energy-dense, nutrient-poor Western diet was recently compared to the current Australian Dietary Guidelines (ADGs) (Hendrie et al. 2014). It was found that while the GHGE for the average Australian diet was 14.5 kg CO_2e per person, the dietary composition of the ADGs resulted in approximately 25 % less GHGEs due to an increase in core, nutrient dense foods (Hendrie et al. 2014). Furthermore, food choice is increasingly becoming an environmental and ethical choice for many people (Boersema and Blowers 2011). Consumers are becoming more aware of the negative impact of greenhouse gas emissions (GHGE) from food production and want realistic and informed choices regarding the emissions from food production. Agriculture plays an essential role in providing food for the world’s population, but food production generates 10–12 % of anthropogenic GHGE, including the majority of nitrous oxide (N_2O) (60 %) and methane (CH_4) emissions (50 %) (Smith et al. 2007). In the European Union, it is estimated that 31 % of GHGE are generated in the food chain (Ericksen et al. 2009). To date there has not been a method for calculating GHGE that is linked to the nutritional value of different foods from agricultural production. The purpose of this paper was to compare specific agricultural systems using several possible metrics for linking GHGE to the nutritional traits or values of foods. We therefore restricted the paper to foods produced in the study region of south eastern Australia.

Metrics commonly used to calculate GHGE from agricultural food production are emissions intensity (t carbon dioxide equivalents (CO_2e)/t product) (Beauchemin et al. 2010; Christie et al. 2011) and emissions in relation to foods' protein content (t CO_2e/t protein) (Aiking 2011). Less commonly, emissions have also been related to the energy content of foods (Pradhan et al. 2013). However, these metrics do not consider other important nutrients in food that are valuable to human health. A possible alternative metric is one that determines the GHGE/unit of nutrient density.

Nutrient profiling has been used to rank food according to its nutritional value. A number of nutrient-rich food indexes have been developed based on nutrient profiling as a scientific method for measuring the nutrient composition of foods and thus providing a means to inform dietary choices (Drewnowski 2005; Drewnowski and Fulgoni 2008; Fulgoni et al. 2009). Nutrient density has previously been calculated in relation to climate impact for beverages where GHGE were divided into the nutritional score of selected beverages, and therefore a high score, showing more nutrients per unit of GHGE, was desirable (Smedman et al. 2010). Hence the metric GHGE/unit of nutrient density can be used to score foods from agricultural production where lower scores are desirable, indicating fewer emissions per unit of nutrient density. In this paper we examine, compare and contrast several metrics that link food production GHGE to nutritional traits.

2 Materials and methods

2.1 Food products and modelled farm enterprises

This study focuses on agricultural food production in south eastern Australia and the emissions generated by producing this food. Therefore the food items chosen were representative of western food staples produced in the study region. Eight food products are examined in this study: lamb from untrimmed or lean cuts, beef from untrimmed or lean cuts, regular milk (minimum of 3.5 % fat), reduced fat milk (1.0 % fat), wheat flour and canola oil. The GHGE of the modelled farm enterprises whose products are transformed into these eight food products are estimated as part of this study. The key characteristics of these enterprises are listed in Table 1. Twelve modelled farm enterprises from south eastern Australia are examined with farm data being drawn from Browne et al. (2011; 2013). The enterprises include sheep, beef and grain enterprises situated at Hamilton (37°16′S, 142°03′E) and dairy farms at Terang (38°16′S, 142°53E).

Livestock enterprises were modelled using the validated mechanistic biophysical models GrassGro (Clark et al. 2000; Moore et al. 1997) and DairyMod (Cullen et al. 2008; Johnson et al. 2008). An 'average' and 'top' enterprise was described for each type of livestock production, based on operating profit per hectare. Top enterprises had higher stocking rates and more improved pastures, as detailed in Browne et al. (2013). The amount of fertiliser applied is listed in Table 1. Using the classification of 'average' and 'top' enterprises allowed the range of emission profiles among farms to be partially described.

Grain yields for wheat and canola enterprises were from the Southwest Farm Monitor benchmark reports for 2002–2011 (Table 1) (Tocker and Berrisford 2010, 2011; Tocker et al. 2009, 2010). Crop rotations and the effects between enterprises were not taken into consideration by this study.

Lamb and beef products were calculated according to the saleable yield of these products, which is the amount of meat that remains once bone and body fat has been removed. Saleable yield was 70 % of carcass weight for both beef (Ball and Johnson 1989) and sheep (Hopkins and Fogarty 1998). The quantity of flour extracted from the wheat crop was 73.3 % (GrainCorp 2011) and canola oil was 45.5 % of crop yield (Riffkin et al. 2012). Milk and canola oil were converted from litres to kilograms at specific gravities of 1.03 and 0.92, respectively (FSANZ 2011).

Table 1 Main attributes of the farm enterprises simulated in this study, based on Browne et al. (2011, 2013)

Enterprise type		Enterprise size (ha)	Stocking rate (animals/ha)	Stocking rate (DSE/ha)	Lambing / calving date	Lambing / calving rates[a]	Sale age—female stock	Sale age—male stock	Fertiliser applied per enterprise	Primary product
Prime lamb	Avg	500	8.3 ewes/ha	19.8	Jul 21	1.11	21–25 wk	21–25 wk	4 t P[c]	Lamb
	Top	700	10.3 ewes/ha	24.4	Jul 28	1.14	20–24 wk	20–24 wk	8 t P	Lamb
Cow-calf	Avg	350	1.4 cows/ha	17.3	Apr 4	0.75	23 mth	9 mth	3 t P	Heifers and steers
	Top	500	1.7 cows/ha	22.0	Apr 4	0.76	23 mth	9 mth	5 t P	Heifers and steers
Steers	Avg	350	2.4 steers/ha	19.7	–	–	–	18–20 mth	3 t P	Steers
	Top	500	2.8 steers/ha	22.4	–	–	–	18–20 mth	5 t P	Steers
Dairy 20[b]	Avg	300	1.7 cows/ha	49.2	Apr 1, Sep 1	0.97	2 wk	2 wk	48 t urea, 30 t DAP	Milk
	Top	270	2.0 cows/ha	58.0	Apr 1, Sep 1	0.97	2 wk	2 wk	72 t urea, 27 t DAP	Milk
Dairy 35[b]	Avg	300	1.7 cows/ha	49.2	Apr 1, Sep 1	0.97	2 wk	2 wk	48 t urea, 30 t DAP	Milk
	Top	270	2.0 cows/ha	58.0	Apr 1, Sep 1	0.97	2 wk	2 wk	72 t urea, 27 t DAP	Milk
Wheat		550	–	–	–	–	–	–	28 t urea, 55 t DAP	Wheat
Canola		250	–	–	–	–	–	–	30 t urea, 25 t DAP	Canola

Avg average farm type, *DAP* Diammonium phosphate, *DSE* dry sheep equivalent, defined as the 8.8 MJ/day of metabolisable energy required for a 50 kg Merino non-lactating sheep to maintain bodyweight, *LW* liveweight, *MFP* milk fat plus protein, *mo* months, *Top* a leading farm in the top 20 % of farms in the region ranked by operating profit/ha (excluding interest and lease costs), *wks* weeks

[a] Lambing / calving rate is the average number of live lambs or live calves born per breeding ewe or breeding cow

[b] Dairy 20 and Dairy 35 enterprises are pasture-based systems that feed 20 and 35 % of total intake from concentrates, respectively

[c] P denotes phophorus applied as single superphophate (8.8 % P)

2.2 Calculation of greenhouse gas emissions

The CH_4, N_2O and CO_2 emissions were calculated using the methodology and emission factors defined by the Intergovernmental Panel on Climate Change (see IPCC 2006), as defined in the Australian National Inventory (see DCCEE 2009 for details on emission factors). On-farm CH_4 emissions were from enteric fermentation, livestock excrement, and burning of crop stubble; N_2O emissions were generated from N fertiliser, livestock excrement and urine, soil cultivation, crop residues, indirect emissions from NO_3 leaching and as NH_3 volatilisation, and burning of crop stubble; and CO_2 emissions were from diesel and electricity use, the latter being generated from black coal. The calculation methods are the same as reported by Browne et al. (2011).

Pre-farm emissions from the production of fertiliser and supplementary feed were included and their emission factors are listed in Table 2. Other pre-farm emissions came from replacement animals that were purchased for the prime lamb and steer enterprises. The remaining livestock enterprises were self-replacing systems that incurred emissions from replacement animals on-farm instead of at the pre-farm level. The GHGE from the production of farm machinery were excluded. Post-farm emissions were from product transportation from the enterprises, animal slaughter and meat butchering, milk pasteurisation and chilling, wheat milling and canola seed crushing (Table 2). The end point of the analysis was prior to and excluding packaging, since there are many different types of packaging available for each product.

Table 2 Emission factors (t CO_2e/unit) to calculate pre and post-farm emissions

Farm input	Emission factor
Grain/concentrates (t CO_2e/t grain)[a]	0.30
Hay (t CO_2e/t hay)[a]	0.25
Urea (t CO_2e/t urea)[b]	0.90
Diammonium phosphate (DAP) (t CO_2e/t DAP)[b]	1.46
Phosphorous (t CO_2e/t phosphorous)[c]	0.90
On-farm diesel (t CO_2e/1000 L)[d]	3.40
On-farm electricity (t CO_2e/1000 kWh)[d]	1.40
Processing milk and cleaning equipment (kg CO_2e/L milk)[e]	0.03
Processing of lamb and beef (t CO_2e/t meat)[f]	1.40
Wheat milling (kWh/t wheat flour)[g]	81.1
Canola crushing (kWh/t canola)[h]	114.5
Transport of farm produce (kg CO_2e/t km)[i]	0.13

[a] Christie et al. (2011)

[b] Centre for Design at RMIT and Life Cycle Strategies Pty Ltd (2010)

[c] Wells (2001)

[d] DCCEE (2009)

[e] Hospido et al. (2003)

[f] MLA (1994)

[g] Zygouras et al. (2005)

[h] CCC (2010)

[i] Williams et al. (2014)

Farms generate multiple products, such as milk and meat on dairy farms or meat and wool on sheep farms, and a percentage of emissions are therefore allocated to each of the products. Mass allocation (Casey and Holden 2005a) was used to assign the percentage of emissions to each on-farm primary product according to the weight of the product sold (Table 3). These primary products are listed in Table 1. Sheep enterprises' emissions were allocated between lamb, mature stock and wool; cow-calf enterprises' GHGE were allocated between heifers, steers and mature stock; and dairy enterprises' emissions were allocated between milk and meat. Emissions were not allocated out for additional by-products such as bone, canola meal or discarded fat from dairy as the carbon liability was assumed to be in the primary process such as milling grain, crushing seeds or processing milk (Table 2).

2.3 Metrics for calculating greenhouse gas emissions from food production

The results were reported using four metrics: emissions/unit of nutrient density, emissions/t product, emissions/t protein and emissions/energy content in gigajoule (GJ). The protein and energy content of the foods studied (kJ/100 g) are listed in Table 4 and the amount of product is shown in Table 5.

Fulgoni et al. (2009) validated six Nutrient Rich Food (NRF) nutrient profile models against a Healthy Eating Index to determine which models most accurately described variations in food. The model that captured most variation was the NRF9.3 model that encouraged nine nutrients and limited three nutrients, hence the NRF9.3 model was used in this study. Nutrient density values were calculated as

$$\mathrm{NRF9.3} = \sum\nolimits_{i=9}\left((\mathrm{X}_{1\text{–}9}/\mathrm{RDA}_{1\text{–}9}) - \sum\nolimits_{j=3}(\mathrm{Y}_{10\text{–}12}/\mathrm{RDA}_{10\text{–}12})/(\mathrm{KJ}/\mathrm{RDA}_{\mathrm{KJ}})\right)$$

where i_{1-9} = protein; fibre; vitamins A, C and E; calcium; iron; magnesium and potassium and j_{1-3} = saturated fat, sodium and added sugar. Each of the encouraged nutrients (X_{1-9}) were divided by the daily Recommended Dietary Allowance (RDA) for the nutrient (i.e. the amount of nutrient considered essential to meet the requirements of healthy individuals). As RDA values differ between males, females and age groups, RDA values for healthy 19–30 year old males consuming 12.4 MJ energy per day were sourced from the Australian National Health and Medical Research Council and these values were compared with 19–30 year old females on a 10.8 MJ per day diet (NHMRC 2006). In a similar way undesirable nutrients (Y_{10-12}), were divided by the RDA for these nutrients. Kilojoule (KJ) is the energy in the portion of food and RDA_{KJ} is the recommended daily kJ intake. The percentage of RDA was capped at 100 % so that food items that had extremely high values of one nutrient, such as the Vitamin E content of canola oil, did not create a disproportionately high nutrient density rating for nutrients in excess of daily requirements (Drewnowski 2005). The nutritional information for each farm

Table 3 GHGE from on-farm, pre-farm and post-farm sources, presented in t CO_2e

	Prime lamb		Cow-calf		Steers		Dairy 20		Dairy 35		Grains	
	Avg	Top	Avg	Top	Avg	Top	Avg	Top	Avg	Top	Wheat	Canola
On-farm	1177	2438	1212	2384	1222	2036	2531	2681	2620	2754	83	58
Pre-farm	496	988	31	34	3541	6103	225	280	246	298	65	71
Post-farm	121	214	62	120	285	494	96	101	110	115	219	38
Total emissions	1793	3641	1304	2538	5048	8633	2852	3061	2976	3168	367	167
On-farm allocated GHGE (%)	64	64	75	74	100	100	86	84	85	85	100	100

Table 4 The nutritional content of nine beneficial nutrients to encourage and three nutrients to limit as part of the nutrient density score

	Nutrient[a]	Lamb[b]		Beef[c]		Milk		Grains		RDA[d]
		Untrimmed	Lean	Untrimmed	Lean	Regular (min. 3.5 % fat)	Reduced fat (1.0 %)	Wheat flour	Canola oil	
	Energy (kJ/100 g)	947	547	763	489	302	212	1498	302	12,400 kJ[de]
Nutrients to encourage	Protein (g/100 g)	19.2	21.8	21.3	22.8	3.3[f]	3.3[f]	10.8[g]	0	64 g[de]
	Dietary fibre (g/100 g)	0	0	0	0	0	0	3.8	0	30 g[de]
	Calcium (mg/100 g)	6	7	5	5	110	112	20	0.9	1000 mg[de]
	Iron (mg/100 g)	1.8	2.1	1.8	2.0	0	0.1	1.5	0	8 mg[de]
	Magnesium (mg/100 g)	22	28	23	25	10	11	34	0	400 mg[de]
	Potassium (mg/100 g)	280	333	339	364	146	161	162	0	3800 mg[de]
	Vitamin A (μg/100 g)	28	18	16	5	113	47	0	0	900 μg[de]
	Vitamin C (mg/100 g)	0	0	1	1	0	0	0	0	45 mg[de]
	Vitamin E (mg/100 g)	0.6	0.5	0.8	0.8	0.1	0.1	0.6	22.1	10 mg[de]
Nutrients to limit	Saturated fat (g/100 g)	6.4	1.6	4.4	1.2	2.4	0.8	0.2	6.2	20 g[gh]
	Total sugars (g/100 g)	0	0	0	0	6.5	6.5	0	0	125 g[gh]
	Sodium (mg/100 g)	56	65	49	55	38	39	2	0	690 mg[de]
	Nutrient density score	4.6	14.9	8.8	18.8	5.0	9.2	5.6	2.8	–

[a] Nutritional information is from FSANZ (2011) unless otherwise indicated

[b] Lamb data was averaged across the following raw cuts for untrimmed or separable lean lamb: chump chop, drumstick, easy carve leg roast, easy carve shoulder, forequarter chop, frenched cutlet/rack, leg roast, loin chop, mini roast and steak (FSANZ 2011)

[c] Beef data was averaged across the following raw cuts for untrimmed or separable lean beef: blade, chuck, fillet, round, rump, sirloin, t-bone and topside steaks; scotch fillet and silverside roast (FSANZ 2011)

[d] RDA, the daily Recommended Dietary Allowance of each nutrient for an adult male of 19–30 years of age to be healthy

[e] NHMRC (2006)

[f] English et al. (2008) and Gilmour et al. (2009)

[g] GrainCorp (2011)

[h] Saturated fat and total sugars figures are maximum daily recommended quantities from Fulgoni et al. (2009)

Table 5 The type of product, quantity (kg/ha) and protein produced (kg/ha) for the 12 enterprises modelled

Enterprise type		Type of product	Amount of product (kg/ha)	Type of low-fat product	Amount of product (kg/ha)	Protein produced (kg/ha)
Prime lamb	Avg	Untrimmed lamb	118	Lean lamb	103	23
	Top	Untrimmed lamb	149	Lean lamb	131	29
Cow-calf	Avg	Untrimmed beef	86	Lean beef	79	18
	Top	Untrimmed beef	117	Lean beef	107	25
Steers	Avg	Untrimmed beef	397	Lean beef	365	84
	Top	Untrimmed beef	481	Lean beef	442	102
Dairy 20	Avg	Milk (3.5 % fat)	8955	Milk (1.0 % fat)	8731	297
	Top	Milk (3.5 % fat)	10,396	Milk (1.0 % fat)	10,136	347
Dairy 35	Avg	Milk (3.5 % fat)	10,215	Milk (1.0 % fat)	9960	338
	Top	Milk (3.5 % fat)	11,981	Milk (1.0 % fat)	11,681	395
Wheat		Wheat flour	2419	–	–	215
Canola		Canola oil	750	–	–	–

Dairy 20, pasture-based dairy enterprises that feed 20 % of total intake from concentrates; Dairy 35, pasture-based dairy enterprises that feed 35 % of total intake from concentrates

product and their RDA values are shown in Table 4. Nutrient density can be calculated either by weight (nutrient density/100 g) or energy (nutrient density/kcal or kJ). Hansen and Wyse (1980) maintained that comparisons between food could only be done on an energy basis because otherwise nutrient density would be distorted by different serving sizes and water content, which influences the food's weight (Buchner et al. 2010). Therefore, in this study nutrient density/kJ was used.

A comparative analysis was conducted between the metrics emissions/unit nutrient density, emissions/t product, emissions/t protein and emissions/GJ to explore the use of each metric when calculating GHGE from food production.

3 Results and discussion

This research estimated the GHGE from 12 farm enterprises that supply primary products used to produce eight food products. The emissions associated with producing these food products were compared using metrics that considered the food's nutrient density, protein content, energy content and weight.

The GHGE produced by the eight different types of food are shown in Fig. 1. Wheat flour produced the least amount of GHGE and meat the most, regardless of the metric chosen. The most variation in results from different metrics occurred in the order of low-fat products: 1.0 % fat milk and lean meat. Lean beef in particular produced the highest emissions in all metrics except for emissions/unit nutrient density.

3.1 Emissions in relation to nutritional content

The benefit of using the metric t CO_2e/unit nutrient density when examining global food requirements was that it accounted more broadly regarding people's nutritional requirements (Drewnowski 2005) whereas other metrics only considered energy or protein requirements. Global population increases have escalated demand for food, land and water resources (Garnett 2011). In turn, food insecurity has lead to malnourishment, micronutrient deficiencies and has further exacerbated starvation in low-income societies (WHO and FAO 2003). Furthermore, of major concern to health

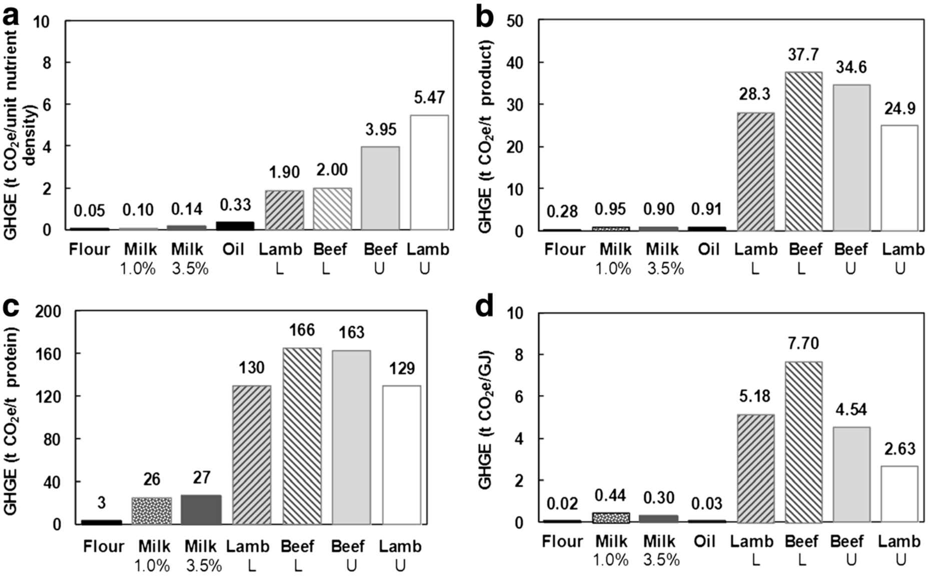

Fig. 1 A comparison of GHGE results using the metrics **a** t CO_2e/unit nutrient density, **b** t CO_2e/t product, **c** t CO_2e/ t protein and **d** t CO_2e/GJ. The values presented are an average figure for the enterprises (Avg and Top). The foods examined were wheat flour, milk with either 1.0 or 3.5 % fat, canola oil, lamb and beef (*L* lean, *U* untrimmed). Canola oil was excluded from the emissions/t protein metric due to canola oil containing no protein

organisations globally is the increase in malnutrition related to over-consumption of energy-dense, nutrient-poor foods that has lead to obesity and related chronic health conditions in both high and low income societies (WHO 2013). Consequently, maximising food production according to the nutritional content of food may become increasingly important.

The foods analysed in this study with the highest nutrient density scores were lean meat and milk (1.0 % fat) (Table 4). Untrimmed lamb and untrimmed beef had nutrient scores reduced due to saturated fat content by 43 and 26 %, respectively. By comparison the deduction in lean lamb and lean beef scores due to unsaturated fat were only 7 and 10 %, respectively. The nutrient density scores for lean meat were also improved by higher values for protein, iron, magnesium and potassium. Despite their high nutrient density scores, the emissions intensity of meat production was 26–42 times higher than the emissions intensity of milk production, which is of concern given that the demand for meat is rising in developing countries (Garnett 2011).

The metric t CO_2e/unit nutrient density was influenced by the recommended daily intake of energy and nutrients. When RDA for 19–30 year old women were used to calculate the nutrient density scores there was less than a 5 % difference between the values calculated for men and women, with the exception of milk and canola oil where the nutrient density score for women was 25–30 % higher and 10 % lower, respectively. While the saturated fat content influenced the outputs for canola oil, the difference in the nutrient density value of milk was driven by RDA values. This included RDAs for protein, fibre, magnesium, potassium, Vitamin A and Vitamin E being lower for women than men, reflecting in a higher nutrient density score of milk for women.

Assuming that encouraging people to consume a healthy diet, whilst limiting GHGE, is the paramount goal of policy-makers and society in general, then our study's key relevant result is that the metric t CO_2e/unit nutrient density is the most effective metric to apply in support of that goal. The metric firstly captures many aspects of dietary guidelines by measuring each food according to how they contribute to daily recommended allowances of a range of nutrients. Secondly, the metric captures the GHGE associated with producing each food product. This metric facilitates the design of daily diets that satisfy dietary guidelines with least GHGE.

Note, a key caveat to this finding regarding the desirability of this metric is that it assumes the main purpose of any metric is to have a healthy diet, as defined by current dietary guidelines, whilst achieving low GHGE. However, in practice policy-makers may have other objectives such as ensuring food remains affordable. Existing research shows that healthy foods cost more than energy-dense foods (Drewnowski and Specter 2004), although this excludes costs of health problems resulting from poor nutrition. Therefore, a food product with a low value of the metric t CO_2e/unit nutrient density may not necessarily be the most affordable in the long-term. Its price will firstly depend on whether or not GHGE are being priced and secondly, on the costs of producing the bundle of nutrients captured in the NRF9.3 measure.

There have been some positive steps to assist consumers in making informed food choices through voluntarily labelling carbon footprints in the UK, but existing labels are often confusing for consumers (Gadema and Oglethorpe 2011). These labels calculate GHGE as g CO_2e / serve (Upham et al. 2011) and are useful when comparing GHGE from similar products, but more confusing when comparing GHGE from different types of products, because serving sizes are often unequal.

In this study the use of emissions/unit nutrient density allowed different food products to be more easily and equitably compared because nutrients were calculated relative to energy in food rather than different portion sizes. The metric t CO_2e/unit nutrient density reflected nutritional differences in similar products as demonstrated in this study when lean and untrimmed meat cuts were compared. This metric (t CO_2e/unit nutrient density) could also be useful for comparing GHGE from the same products where a different mode of production causes nutritional differences in food products. By illustration, in pasture versus grain-fed beef, pasture-fed cows can produce beef with higher nutritional values (Descalzo et al. 2005), which would then have to be compared against the higher amount of GHGE that pasture-fed beef cows tend to produce due to greater roughage in the diet, even when emissions from growing grain for animal feed are included (Beauchemin et al. 2008).

Emission intensity (t CO_2e/t product) is a common metric for analysing product-based GHGE but this metric does not reveal important differences in food products and hence their value to human nutrition. Since products are reported according to their weight, the water content in food has an impact on the results. Fruit and vegetable products in particular have high water contents which can affect an emissions intensity metric. Milk also has a high water content which is why agricultural emissions research from dairy farms usually defines the product using calculations based on the fat and protein content of milk, such as milk fat plus protein (Browne et al. 2011) or energy corrected milk (Casey and Holden 2005b; Christie et al. 2011). However, when the metric t CO_2e/unit nutrient density is used, the results are not as affected by water content because the NRF9.3 nutritional value is calculated per kJ, creating a less distorted comparison of the nutritional content of food, rather than the weight of food.

3.2 Emissions in relation to protein content

Protein is an important nutrient in food. Using the metric emissions/t protein, meat products still produced the highest emissions, despite the high percentage of protein in lamb (19.2–21.8 %) and beef (21.3–22.8 %). Dairy and wheat farms produced 2–22 times more protein / hectare than beef and lamb (Table 5), although not in the same concentrated form that meat provides. However, meat does also provide other nutrients. It has relatively high nutrient profile scores (NRF9.3 = 14.9–18.8) when presented as lean meat, otherwise nutrient scores are comparable to milk and wheat flour (Table 4). This is consistent with current dietary recommendations to consume lean meat, in preference to untrimmed meat, but limit intake of meat products that are high in saturated fat (NHMRC 2013). Numerous studies have shown that less emissions intensive protein sources are available (Aiking 2011; Garnett 2011; Gonzalez et al. 2011; Smil 2002b), but social values of meat consumption may need to be addressed first if consumer choices are to change to high plant-based protein products that produce less GHGE (Boersema and Blowers 2011). Tukker et al. (2011) demonstrated that the consumption categories for individuals most pertinent to global warming are meat, dairy and transport. Our results however, do not confirm this for dairy when using t CO_2e/unit nutrient density or the other metrics in this study. The difference in results is due to the product being reported on. In this study we have calculated values for milk, yet Verge et al. (2013) have reported that for dairy production in Canada, products such as cheese, powders and butter have 5, 10 and 7 times higher emissions (t CO_2e/t product), respectively, than fluid milk.

Although protein is important for human health, protein consumption in developed countries is in excess of what is required (Smil 2002a), while diets are simultaneously deficient in crucial vitamins and micronutrients (Kant 2000). The use of a nutrient density metric to calculate GHGE (t CO_2e/unit nutrient density) considers a wider range of required nutrients, especially those nutrients that may be lacking in the human diet, rather than protein alone. Emissions/unit nutrient density is therefore a more comprehensive metric to use when focusing on the GHGE produced by food when trying to improve human health.

3.3 Emissions and energy in food

The metric emissions/GJ explored the energy content of food and predictably, those foods high in fat and therefore kJ, produced less emissions than similar low-fat products. This metric does not limit saturated fats thus does not equitably compare the nutritional composition of foods high in different types of fats (i.e. saturated vs. unsaturated fats) and therefore similar energy content. In developing countries the number of kJ consumed is often below what is required to sustain adequate growth and development, leading to the undernourishment of millions of people in developing countries (Conway and Toenniessen 1999). A range of health problems are widespread from inadequate nutrition in developing countries, particularly in women and children (UNICEF 1998). An increase in available funds, often coupled with decreased nutritional knowledge, is often associated with a rise in malnutrition due to greater consumption of highly refined, energy-dense, nutrient-poor, non-core foods that are particularly high in saturated fats and often associated with the ‘wealthy Western lifestyle’, which may lead to obesity and related chronic health problems such as diabetes, heart disease and an increased risk of certain cancers (WHO 2013; NHMRC 2003). Obesity or being overweight is the fifth highest risk for deaths in the world (WHO 2013). Furthermore, health conditions associated with over-consumption are not only prevalent in high-income societies, but are increasing in developing societies as well. It is a challenge to simultaneously reduce the rise of over-consumption of highly refined energy-dense foods in both the developed and developing world while ensuring adequate availability and food security to people in low-income societies (WHO 2013). The emissions/unit nutrient density metric includes a deduction for saturated fat, sodium and added sugar to account for negative health effects of over consumption, thus would be a more equitable metric than just using emissions/GJ. While those who are undernourished due to inadequate food supply do not need to reduce kJ intake, using a nutrient density measure when calculating GHGE (t CO_2e/unit nutrient density) addresses nutritional requirements for malnourishment resulting from either over- or under-consumption of food.

3.4 Future areas of research

Further research would be useful that extends the use of this nutrient density metric beyond the limited number of agricultural products farmed in the study region to a wider range of food products and levels of processing. While the results from this study are applicable for farms elsewhere in the world with a Mediterranean environment and similar stocking rates, it will be important to examine the use of this metric in regions with different amounts of rainfall, especially more extensive systems with lower rainfall and stocking rates. There are also important environmental impacts to consider such as the water use of different types of agricultural production, with meat production requiring more water and environmental resources than vegetables or grains (Buchner et al. 2010), although grain farms introduce other environmental issues such as soil degradation and reduced soil carbon levels (Chan and Bowman 1995). These environmental impacts were outside the scope of this research.

4 Conclusion

This study used four metrics to compare the emissions profile of wheat flour, milk (1.0 % and 3.5 % fat), canola oil, lean lamb, lean beef, untrimmed lamb and untrimmed beef. The metrics were t CO_2e/unit nutrient density, t CO_2e/t product, t CO_2e/t protein and t CO_2e/GJ. Emissions/unit nutrient density (t CO_2e/unit nutrient density) was the preferred metric in situations where the main policy goal was to encourage adherence to dietary guidelines whilst limiting emissions. The metric allowed comparison of different types of products on the basis of their nutritional value, rather than according to singular nutrients such as protein, or specific attributes such as product weight or energy content. The metric emissions/unit nutrient density has the potential to inform consumer choices regarding foods that have a higher nutritional content compared with the GHGE generated, assuming this metric can be presented to consumers in a clear manner that is easy for consumers to understand. The production of beef and lamb generated the highest emissions (t CO_2e/unit nutrient density), followed by canola oil, milk and then wheat.

A more complete analysis of this metric incorporating a larger number of foods would be helpful to understand its impact on a wider range of foods and levels of processing. Further analysis is also required to determine if this metric is suitable for areas where food is scarce and energy requirements are not met and where the consumption of additional kJ in food may be desirable. The metric emissions/unit nutrient density may also benefit from further examination into the numerous methods of calculating nutrient density scores (Drewnowski 2009; Drewnowski and Fulgoni 2008; Fulgoni et al. 2009). Widening the review of the desirability of this metric when other policy considerations apply, such as the expense of food, or environmental factors such as water use, are also a potentially worthwhile extension of this study.

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