The carbon footprint of meat and dairy proteins: a practical perspective to guide low carbon footprint dietary choices

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Meat and dairy products in the food industry represent a significant portion of anthropogenic green house gas emissions. To meet the Intergovernemental Panel on Climate Change recommendations to limit global warming, these emissions should go down. Meat and dairy products are also responsible for the majority of our daily, vital, protein intake. Yet, meat and dairy products contain very different amounts of proteins, making it difficult in general to rationalize which protein source has the lowest carbon footprint. Here we offer a practical and pedagogical review, comparing the carbon footprint of a variety of meat and dairy products with respect to their protein content. We report further on a number of consumer-oriented questions (local or imported? organic or not? cow or goat milk? hard or soft cheese?). We investigate finally the carbon footprint of different dietary choices for several countries, by keeping the total number of meat and dairy proteins constant. Dairy-only diets are in general a little less carbon intensive than current diets; while up to 60% lower carbon footprint diets can be achieved by eating for only part poultry, small animals and yogurt. Our assembled data is readily available through an open source app allowing to investigate personalized dietary scenarios. We expect our results to help consumers perform enlightened carbon footprint dietary choices. Our methodology may be applied to broader questions, such as the carbon footprint of proteins in general (including fish and plant proteins). We hope our work will drive more studies focusing on consumer-oriented questions.

I. INTRODUCTION

Climate change, resulting from the emission of greenhouse gases by human activities – in particular carbon dioxide, is a worldwide threat with long-lasting implications[1]. To limit the increase of global average temperature compared to preindustrial level, substantial efforts have to be made. Indeed, according to the Intergovernemental panel on climate change (IPCC), limiting global warming to 1.5°C requires to reduce the emissions by 45% from 2010 levels by 2030, and to reach net zero by 2050[1] – see Fig. 1. Even limiting global warming to 2.0°C brings these numbers to a 25% decrease of emissions in 2030, and to reach net zero in 2070[1].

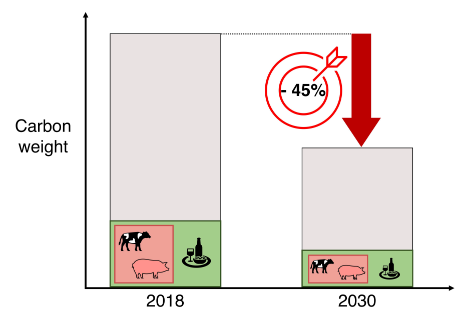

FIG. 1. Illustration showing the proportion of food and meat based products in the global carbon impact balance of anthropogenic emissions and the relative change recommended by IPCC.

A. A brief on CO_2 emissions of food

Per year, the food supply chain generates 13.7 billion metric tons of carbon dioxide equivalents (CO_2 eq.)[2]. That represents 26% of the total anthropogenic green-house gas (GHG) emissions[2]. Furthermore, significant increase of food chain related emissions is expected with population increase and income level increase[3]. Therefore, in line with IPCC guidelines, reducing the emissions of the food supply chain seems critical[3–5].

Among the food supply chain, meat and dairy production generates a significant amount of GHG emissions. Livestock alone represents at least 14% of the total world emissions[5–7]. More than half of the emissions from food stems from livestock because a number production steps are carbon intensive. For example, to produce beef, everything that happens at the farm (methane emissions from cows, farm machinery) represents on its own 66% of the emissions[2]. Land use change (initial deforestation to create a pasture, and subsequent soil contamination) represents 27 %[2] and animal feeding (growing crops to feed livestock) represents 3 % . Transport, processing, packaging and retail fill up the remaining categories (so the remaining 4%).

But just how much meat does that represent in the consumer's plate? Meat consumption for an American averages to 120 kg of meat per year[8], corresponding to about 340 g of meat per day. Note that this amount does not take into account food loss at the consumer level such that the actual amount of food eaten may be lower (*i.e.* food loss at retail stores, in restaurants and household waste which have been estimated to be at least 30% in weight[9]). This value falls to $210 g/day$[8] in the European Union, $160 g/day$ in China and the world av-

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erage is $115 g/day$[8]. Calorie wise, taking a typical number of $200\ kcal/100g$ of meat[10], beef represents 8-24% of total calorie intake[11 12]. This is a relatively small fraction considering it accounts for more than half of the carbon footprint. This imbalance between actual calories provided and carbon footprint can be further illustrated by the following number. In the United States (US), 4% of food sold (by weight) is beef, but that represents 36% of food-related emissions in the country[13].

All in all, meat and dairy products represent the most relevant food category contributing to the total carbon footprint of dietary choices. A critical common point of meat and dairy products is that they are foods with high protein content, and are therefore primary sources of protein in current diets. In the following, note that we will also include eggs in the "dairy" category as they represent a significant source of protein in common diets.

B. What are proteins, why do we need them and just how much ?

Proteins are large molecules made up of chains of amino acids. When we digest proteins, we break them down into amino acids – see Fig. 2. Amino acids achieve vital functions in our body – for example some are used for neurotransmission[14]. Amino acids can be further broken down to produce energy to power our body[15] (and the rest of the pieces – urea and carbon dioxide – are eliminated by urine and breathing). Finally they can also be reassembled by the organism to synthesise other kinds of proteins that achieve a number of other vital functions in our body[14]. In short, it is impossible to live without proteins.

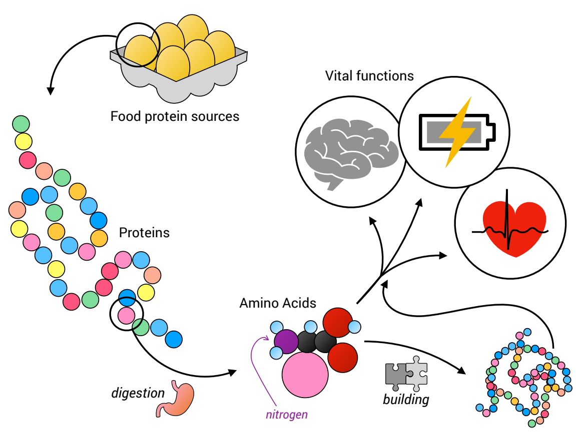

FIG. 2. Illustration of the cycle of proteins and amino acids in human nutrition and their use in several vital functions.

Typically, for a person in good health (and that does not do any major sport training), the globally established dietary reference intake is about 0.8 g of protein per kilogram of body weight per day[11,16])[17]. This means that a person weighing 60 kg (132 pounds) needs about 48 g of proteins per day, or a person weighing 80 kg (176 pounds) needs 64 g of proteins per day.

Higher values of protein intake per day can be beneficial in some circumstances. Up to 2.0 g/kg/day is beneficial to maximise muscle protein synthesis in resistance-training adults, with a maximum of 0.4 g/kg/meal[18]. Furthermore it is a common misbelief that a high protein diet – alone – can impact bone health[19,20]. For the elderly, muscle strength preservation can be improved by protein intakes up to 1.0 g/kg/day accompanied by safe endurance and resistance type exercises[21,22].

High *animal* protein intakes may however be connected with some specific diseases. For instance, high intake of *animal* protein – from 0.8 g/kg/day and over – may be connected to some age-related diseases (cancer, diabetes, cardiovascular diseases)[23–26]. This is especially true for red meat (beef, pork, mutton and lamb) and even more so for processed meat[23,27]. Substitution of animal protein by plant protein is beneficial to reduce overall mortality[25]. Of course, this substitution must still result in an adequate protein intake. Indeed an insufficient protein intake can also yield age-related diseases, especially muscle loss[23]. Note that adequate protein intake from plant sources is possible as all necessary amino acids may be found in plant based foods (especially in soy and legumes like lentils)[16,2829].

To put these numbers in perspective, in the US, it appears in average people eat $1-1.5$ g/kg/day of protein[3031]. Out of these, about 60% are meat and dairy sourced proteins[32], and therefore meat and dairy represent the most important source of proteins in current diets. Thus it is only natural to investigate the carbon footprint of meat and dairy proteins.

C. Scope of this study: the carbon footprint of meat and dairy proteins

For all these reasons, we investigate here the carbon footprint of meat and dairy proteins. Inspired by the works of[2,33,34] we aim for a measure of the carbon impact per gram of protein for these different sources. This allows to directly compare different sources of proteins and determine which ones are the least carbon-impactful (section II). This is aligned with our goal of making a consumer-oriented review. To make the data generated accessible, we design an open-source web based application to evaluate efficiently the carbon footprint of different dietary choices. Furthermore, we review a number of consumer-type questions associated with meat and dairy consumption: such as the choice between local or imported products, organic or non-organic, cow or goat milk, *etc.* (section III). To complement our research, we investigate how different dietary choices – *restricted to meat and dairy proteins* – across countries may drastically change the carbon footprint of the diet (section IV).

We stress again that here we focus specifically on meat and dairy proteins. As mentioned earlier, not only do they represent the most abundant source of protein and the most carbon impactful part of our diets, but a number of relevant consumer-oriented questions have to be addressed for these food categories. Fish and plant proteins are beyond the scope of this review. Finally, in line with our desire to answer consumer-oriented questions, we have adopted a pedagogical style throughout.

II. THE CARBON FOOTPRINT OF MEAT AND DAIRY PROTEINS

A. Methodological aspects

For this study we retain only the most common meat and dairy protein-rich products (discarding especially those for which data availability is limited). Among meat products, we explore the carbon footprint of beef, lamb, veal, pork, turkey, chicken, rabbit, duck and among dairy products we explore cow-based dairy: milk, cheese and yogurt; and finally chicken eggs. Different dairy sources (such as goat, sheep and buffalo) are compared, among other more focused questions, in the section III.

a. Protein content. Protein content range for the products investigated was taken from various national databases[10,35–37] – making sure that the methods for protein quantification in foods[38] were consistent. More information on the methods and the data retained in this study can be found in Appendix A. The protein content of the different products is presented in Fig. 3-a. While for most (unprocessed) meats the protein content range is roughly similar, around $20g/100$ g(edible), the protein content of dairy products is very broad, ranging from $3g/100$ g(edible) for milk to $36g/100$ g(edible) for some specific hard cooked cheeses. Within a single food category, the range itself can be very broad (from $17-36g/100$ g(edible) for cheese products – excluding for now cream cheese or cottage cheese that go as low as $8g/100$ g(edible)). This highlights the importance of a quantification of carbon impact per g of protein.

b. Carbon footprint. Carbon footprint range for the products investigated was taken from meta-analyses of life cycle analyses (LCA)[2,39,40] and complemented with national databases for extreme value assessment[41,42] – making sure that the methods for carbon footprint calculation were consistent. More information on the specific methods and data retained in this study can be found in Appendix B. The carbon footprint per edible weight of the different products is presented in Fig. 3-b. Some food categories have exceptionally large carbon footprints, such as meat from beef, lamb and veal, ranging in average from $2-6kg\,CO_2\,$eq.$/100$ g(edible)). Other foods have specifically small carbon footprints, in particular lightly processed dairy products such as milk and yogurt, with about $100-300g\,CO_2\,$eq.$/100$ g(edible). Yet, as mentioned earlier, these products have clearly different protein content as well, and therefore these extreme differences will be greatly reduced when reporting on the carbon footprint per g of protein.

c. Carbon footprint per g of protein. To assess the carbon footprint per g of protein we divide values of carbon footprint (per g of edible weight) by protein content (per g of edible weight). As both carbon footprint and protein content are ranges, we obtain several ratios – see Table I. We present the data with center values and uncertainty ranges based on geometric averages of those ratios. The use of geometric averages is favored over arithmetic averages for better data acknowledgement and to avoid data distortion by extreme values[43,44] – see Appendix C.1. for more details. The results are summarized in Fig. 3-c.

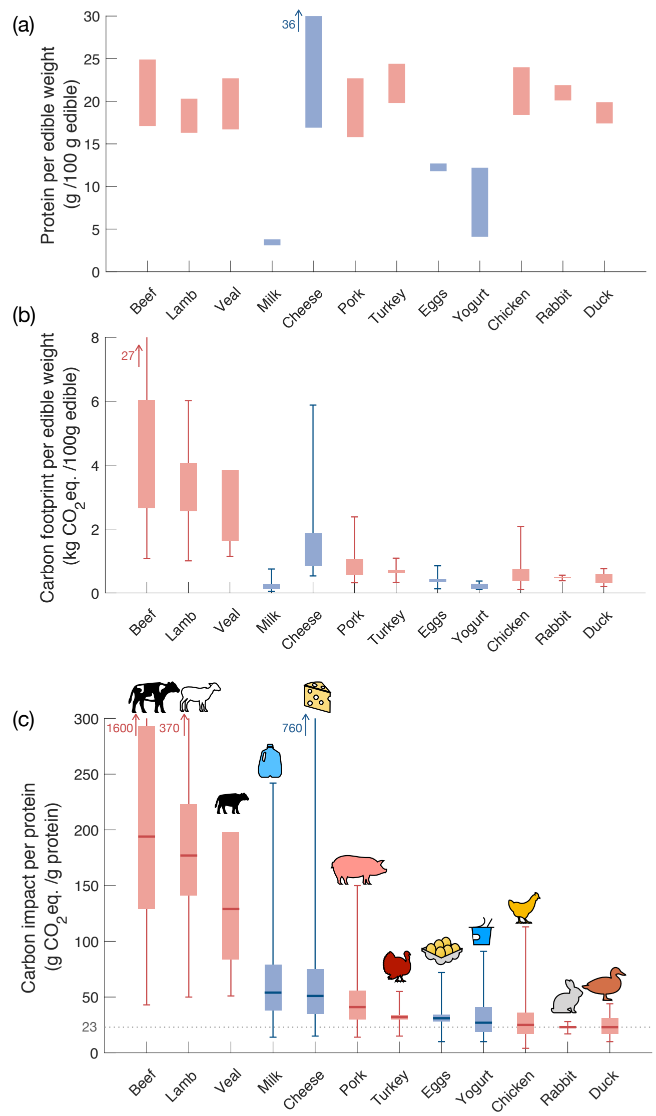

FIG. 3. Comparing the carbon footprint of various animal proteins. (a) Protein content range retained in this study for different meat and dairy products. (b) Carbon footprint range and errors retained in this study for different meat and dairy products. (c) Carbon impact per g of protein as calculated from (a) and (b), methodology described further in the text. The dashed grey line is an indicator line corresponding to the lowest value of carbon impact per g of protein found in this study.

TABLE I. Protein based carbon intensity of common meat and dairy products (sorted from the most impactful to the less). C refers to carbon footprint, P to protein content and m to median. All quantities are given in g_{CO_2} eq./g protein. The average carbon intensity is calculated from the geometric average of the 4 previous columns, while the uncertainty range is given by the geometric average of the 2 first and 2 last columns.

Product	$\frac{C_{m,min}}{P_{max}}$	$\frac{C_{m,min}}{P_{min}}$	$\frac{C_{m,max}}{P_{max}}$	$\frac{C_{m,max}}{P_{min}}$	Average
Beef	107	156	243	353	194 (129-293)
Lamb	126	157	200	249	177 (141-223)
Veal	72	98	170	231	129 (84-198)
Milk	34	42	71	87	54 (38-79)
Cheese	24	51	51	110	51 (35-75)
Pork	25	36	47	67	41 (30-56)
Turkey	28	32	32	36	32 (30-34)
Eggs	27	29	33	36	31 (28-34)
Yogurt	11	32	24	70	27 (19-41)
Chicken	15	20	31	41	25 (17-36)
Rabbit	21	23	22	24	23 (22.4-23.2)
Duck	16	18	29	34	23 (17-31)

B. Main results: carbon footprint per g of protein

Figure 3-c and Table I recapitulate the main results of our analysis, showing carbon footprint per g of protein for most common, protein rich, meat and dairy products. The data is sorted from the product with the highest carbon footprint per g of protein to that with the lowest. The results we find are comparable to refs. 2, 33, and 34 for the few categories investigated.

1. Insight from carbon impact per gram of (meat or dairy) protein

In Figure 3-c we observe that some foods that have comparable protein content (such as meats) have very different carbon footprints per g of protein. This is mostly due to their initial very different carbon footprints per g of edible food – spanning 2 orders of magnitude from $20 g CO_{2,eq}/g$ for chicken, duck and rabbit to $200 g CO_{2,eq}/g$ protein for beef. The difference between different meats is mostly due to the fact that some animals (beef, sheep, veal) are *ruminants* and emit large quantities of greenhouse gas through manure emissions. This is not the case for other animals such as pig, chicken, rabbit and duck. Another interesting result is that in general larger animals have a larger carbon footprint per g of protein. A consumer's oriented take-away rule (in line with low carbon footprint goals) is thus to favor meat from smaller animals.

Figure 3-c is especially useful to compare foods that have very different protein content such as milk and beef. Milk has the lowest carbon footprint per g of edible food among all the foods considered here. Yet it also has the lowest protein content, making direct comparison with meat difficult. Our Fig. 3-c shows clearly that milk has a relatively high footprint $60 g CO_{2,eq}/g$ protein, with extreme values ranging higher than the average value for beef. This clearly shows that to compare the carbon footprint of protein-rich foods, it is extremely useful to use such methodology. Interestingly, cheese carbon footprint per g of protein ranks very closely to milk, with an impact twice as high as *e.g.* chicken. This hints that lacto-ovo-vegetarian diets (abbreviated thereafter to vegetarian), based on high intake of dairy products such as cheese or milk, may not be as effective in reducing carbon footprint as other more carefully designed alternative diets. Such alternative "low carbon diets" could *e.g.* include chicken and exclude carbon intensive meats such as beef.

There are a number of other meat and other dairy products available on the market. Among these, game meat – often a locally bought meat – may appear as a low carbon alternative. In fact, game meat is not taken into account in national carbon assessments, because the Kyoto protocol considers that game meat is part of the ecosystem and does not contribute to *anthropogenic* carbon emissions[45,46]. Be that as it may, it is interesting to note that ruminants such as deer emit comparable, high amounts of greenhouse gas, much like their mass-produced counterparts, such as beef and lamb[47].[48]

We now come back to comparing (cow's) milk and beef/veal. Milk and meat are the two main products generated by cow breeding. In a protein-focused perspective, one might expect that eventually milk and beef – that come from the same animal – should have the same carbon impact per g of protein. Yet that is not the case, because of the way carbon footprint is allocated to the different sub-products. We discuss this further in the following section.

2. Milk or beef steak? A note on carbon allocations

When comparing the carbon footprint of different foods, it is crucial to note that there are different ways to distribute carbon emissions among sub-products (*e.g.* milk or beef)[2]. In line with our pedagogical view we take here a concrete – admittedly very simplified – illustration. Let's consider a dairy cow in a farm. When breeding the cow, a number of processes (feeding, grazing, manure...) result in a total carbon footprint for the cow per year. After a few years, the cow will have produced a certain quantity of milk and meat. Just how much of the total carbon emitted will then be attributed to the meat or the milk is called *carbon allocation*. In the context of our study comparing protein-rich foods, we ask if there is a better way to allocate carbon.

To take the example further, we consider the carbon footprint per g of protein for beef and milk with two allocation scenarios: (1) if carbon were allocated on a protein basis versus (2) an economic allocation. A dairy cow produces about 26000 kg of milk for 190 kg of edible meat[49]. To determine allocations in (1) we need to know the total proteins produced.

Taking data from Table IV and V (retaining 20g protein/100g of edible meat for meat and 3.3 g protein/ 100g of milk) we get a total of 858 kg of milk protein and 38 kg of meat protein, so a ratio of 96%. If the cow produced say 100 carbon units, that means that any kg of (cow-sourced) protein is 0.112 carbon units with protein allocation (1)[50]. To determine allocation in (2) we need to know the relative economic value of products. Taking a price of 0.9$\$/kg$ of milk and 11$\$/kg$ for meat[51] makes a total price of 2090 dollars of meat and 23400 dollars of milk, thus a ratio of 92%. Thus the economic allocation (2) attributes 92 carbon units to milk (respectively 8 to meat), making 0.107 carbon units per kg of milk protein (92/858) and 0.211 (8/38) for meat protein. The results are summarized in Fig. **??**. Note that the coarse-grained numbers calculated here give a good representation of more advanced analyses[2,52]. We find that milk proteins have similar carbon footprints regardless of the allocation method. In contrast meat proteins have higher carbon footprint with economic allocation, nearly twice as high as milk proteins. Indeed, in dairy farms, the amount of meat is just so little compared to milk that protein allocation tends to *underestimate* the carbon impact of meat.[53]

In light of these very different results with different allocation methods, one may wonder which allocation method is the "best". In general, allocation by the amount of protein (method 1) or (more commonly used) by the amount of energy (calorie content) is not relevant. For example, in many situations the same initial compound may be used for outputs that are not comparable protein-wise or calorie-wise. For example milk, can be used to make whey protein (very high in protein, quite low in energy) or butter (very low in protein, very high in energy). A protein based-allocation would therefore have butter be nearly carbon-free[54]. Carbon allocation based on the relative price of the products – *economic allocation* (method 2) does not suffer from these limitations. In fact, economic allocation has the advantage of drawing more carbon intensity to more demanded products. It also lightens carbon weights of less demanded co-products such as whey or straw. For the numbers retained in our study, analysis is in fact based on economic allocation.

Although our example was focused on the simplistic example of allocation for milk and beef, carbon allocation concerns much more products and in particular dairy sub-products. In fact, once the carbon footprint of milk is calculated, allocation has to be distributed between sub-products such as cheese, butter and whey powder[52]. Taking into consideration much less demanded by-products such as whey powder during cheese production[55] can greatly reduce the carbon impact calculated for cheese. As seen earlier, the allocation protocol at each stage greatly also influences the final result[52]. We come back to dairy sub-products in Sec. III.

Finally, for further comparison of allocation methods we refer the reader to[2,52,54–56].

III. A LOW CARBON FOOTPRINT CONSUMER GUIDE

Building on our efforts to compare protein-rich foods, we now explore how our results and methodology can be extended to provide an actual low carbon footprint consumer guide between protein-rich foods.

A. Online tool to guide low carbon footprint dietary choices

The first natural question that a consumer may ask is to know which protein foods are the least carbon impactful. As part of a dissemination effort, we have built a simple online tool – see Fig. 4 and Ref.[57] – allowing anyone to estimate their carbon footprint from meat and dairy products. The tool requires the user to enter their weekly consumption of the most common meat and dairy products in a single online interface. It then returns the carbon footprint of those products, comparing it to the average European Union (EU) value – see Sec. IV. It also gives the corresponding daily protein intake, comparing it to the European Union average value. Fig. 4 shows an example close to the typical EU diet.

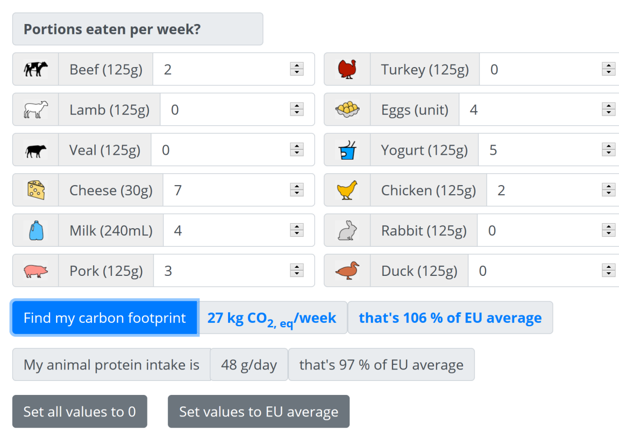

FIG. 4. Example use of our online tool[57] (accessible at `http://www.sciriousgecko.com/ArticleMeat.html`) for a quick assessment of the carbon impact of meat and dairy proteins.

The data used to compute the carbon footprint and protein intake is taken from Tables IV, V, VI and VII with a methodology similar to the one detailed in Sec. V. To compare to average EU data, we must take into account food losses. In fact, average EU consumption data are based on retail sails and not on consumer consumption. We therefore correct the carbon footprint obtained from the user's consumption by adding a 30% factor, consistently accounting for food losses within the approach by Shepon *et al.*[9]. Note that food losses especially for meat can be much higher (up to 96% for beef). The source code is freely available[57].

When buying meat or dairy, beyond the question of *which* product to by, a consumer may be able to choose *where* and *how* the product was made. To guide a low carbon impact purchase, we review these questions in the context of meat and dairy products in the following subsections.

B. Local or imported meat ?

Consumers are generally keen on buying and consuming "locally" produced foods[58,59]. Key driving factors include – but are not restricted to – associating health and quality with local products[58,59], concerns of helping the local economy to thrive and engaging in sustainability[59,60]. Carbon footprint being one of the aspects of sustainability, it is a natural question to ask, when buying meat or dairy, if "local" makes a difference in terms of carbon footprint.

For *ruminant* meat and dairy, transport typically represents an infinitesimal fraction of the carbon footprint[2,45,61–63]. In fact breeding, crop growing for feeding and manure emissions represent significantly much more emissions[2,45,63]. As a canonical example, a study showed how dairy (resp. lamb) imported to the United Kingdom (UK) from New Zealand could actually be 2 (resp. 4) times less carbon intensive as dairy (resp. lamb) directly produced in the UK[61 64]. In this example, the impact of food miles from New Zealand to the UK is greatly compensated by a more efficient production system in New Zealand. In fact the majority of food miles are achieved via refrigerated sea transport, which is largely less intensive than other road or airborne miles[61,62]. As a rule, production methods are the main factor determining *ruminant* meat and dairy proteins' carbon impact.

However, when specializing into sub-products of the dairy industry such as cheese, reducing the transport footprint may significantly reduce the carbon footprint of the product overall. In fact, to make cheese, one requires either raw (liquid) milk or curd – a substance obtained from milk after coagulation. Curd is much lighter than the initial total milk required to make it. Therefore transporting curd instead of raw milk before processing can have significant impact on the overall carbon footprint of cheese (15% reduction is reported in[56] for the production of mozzarella in the Italian dairy sector).

While for ruminant meats and eggs, emissions linked to transport remains under 2% of the total, for poultry and pig meats they average at about 5%[2]. Therefore, consuming locally sourced pork and poultry (or transported with low-carbon footprint means) is consistent with a low-carbon intensity endeavor.

To put in a nutshell – apart from ruminant meats and dairy for which the question has to be sorted on a case by case basis[4,63] - all other protein-rich meat products have generally a lighter carbon footprint if produced locally.

C. Organic or non-organic ?

Consumers also show increased interest in buying organic food products, including for meat and dairy products[65–67]. Similarly, when trying to minimize carbon impact, one may ask which agricultural method is the best (here we will focus on organic versus non-organic). In contrast with to the question of transport, comparing different agricultural methods is a challenge due to the limited availability of data and the difficulty to compare different life cycle analysis (LCA) at this level of accuracy. Here we review a few results from authors directly comparing organic and non-organic systems.

We first tackle the subject of ruminant meat and dairy. A study on a farm in japan found that the global warming potential of organic versus conventional systems for beef was similar[68]. In the UK, organic beef and dairy emits about 15% more than conventional farming[45], while organic sheep farms emit 42% less CO_2. In Italy, a case study found that organic beef emits even up to 30% more[69]. A meta-analysis conducted recently reveals that organic cow milk emits 10% less CO_2 than conventional[70]. The broad variety of results makes it difficult to conclude on a general trend. Furthermore, when comparing organic versus non-organic ruminant farms, the results strongly depend on the allocation method and on the method used to account for land use change[71]. They also depend strongly on the specifics of organic farming, and whether modern organic farming techniques are used or not – in particular for manure management[72].

However the different studies agree on the relative impact of sub-contributions of cow breeding. For instance organic livestock is locally grass-fed with high quality grass (with more clovers and so on)[45,68,70]. Food does not need to be brought from elsewhere, resulting in a decrease of emissions for the organic system. Still, the amount of grass required for grazing is more important, resulting in more land use change; often organic grass is also treated with manure and other organic fertilizers that emit more carbon[45] – although that depends on manure management[72]. Other authors suggest that the different type of feeding results in more enteric fermentation in the organic feed[69]. Noteworthy, optimization of production by larger farms does not seem to impact significantly the carbon footprint of dairy production[73]. The variability in the relative importance of these factors explains the variability of the results for organic versus non-organic ruminant products.

For non-ruminants such as poultry or pork, data availability is even more scarce. In the Netherlands a study reports that organic pork production emits between 8 and 40% more carbon than conventional[74], while in the UK organic pork was found to emit 11% less [45]. For poultry in the UK, organic farms emit 46% more CO_2 and free-range non organic (versus cage non organic) emit 20% more than conventional[45]. Similarly for eggs in the UK, organic farms emit 27% more CO_2 and free-range non organic farms emit 12% more than conventional[45]. In the UK, "optimized" breeding in conventional farms, relying on an efficient use of space, explain the relative better performance of conventional methods[45]. Another important contributing factor is more important grazing in organic systems, that tends to increase emissions[74].

One important common feature between ruminants and non-ruminants is that the question of the environmental impact of organic versus non-organic agriculture is much broader than just the carbon footprint. Livestock breeding deteriorates soil and water quality (in the form of water and soil eutrophication (increase of nutrient composition, that can disturb the balance of life forms) and acidification). Such deterioration is generally more important in organic farms that rely on more ground use than non-organic farms[45,74]. However non-organic products require in particular more synthetic pesticides[45,72], which have their own detrimental environmental impact[75,76]. Noteworthy, organic livestock breeding – and other "sustainable" breeding approaches – can be beneficial in many more ways (such as introducing nitrogen fixing plants to enhances soil quality), that are further detailed in[72].

The current data on organic versus non-organic production systems suggests that in general organic meat and dairy production leads to a higher carbon impact than non-organic, especially via land use change – unless modern techniques are used[72]. However, the "organic" criteria for products strongly depends on respective country laws. Non-organic farms also strive to consider "sustainable" farming approaches that do not necessarily require organic farming[72]. As described above, there is large variability and more in-depth studies are required to assess the climate impact of organic versus non-organic meat and dairy farms.

D. Specializing into dairy products: milk, cheese, yogurt, whey ... and butter

Compared to meat, the variety of dairy products (high in protein content) is quite large: from milk with different skimming contents, to yogurts with added fruit or reduced fat, and the never ending array of cheese options. Furthermore, dairy can be derived from different animal milks. Among all these high protein dairy products, a consumer may wonder which one to choose to achieve the lowest climate impact target. This is what we address in the following paragraphs.

1. *Cow or goat milk ?*

Milk production around the world originates from different sources. For example, although cheese production across the world is essentially made of cow milk (94%) a small fraction of cheese is made from sheep (3%), goat (2%) and buffalo (1%)[77]. Therefore, one may wonder which source of milk is less carbon intensive among these different animals. Here we review the carbon impact per gram of protein of these different milks. We adopt the same methodology as the one used to obtain the main results of this paper as presented in Sec. II B.

Comparing different milk sources is especially interesting since the protein content of milk varies among species – see Fig. 5-a. In particular, sheep milk has a protein content about 2 times larger than cow, goat or buffalo milk. However, the carbon footprint per edible weight of sheep milk production is also the largest among these species – see Fig. 5-b. Overall this results in only slight differences between species when comparing the carbon impact per g of protein – see Fig. 5-c and Table II. Cow's milk is the less carbon intensive per g of protein (potentially due to a generally more optimized production line, cow's being the species most commonly used), closely followed by goat and sheep milk. Finally buffalo milk seems to be the most carbon intensive per g of protein, nearly twice as high in average as cow's milk. This final comparison comes with some uncertainty as limited data is available for buffalo's milk.

TABLE II. Protein based carbon intensity of various milks (sorted from the least impactful to the most). C refers to carbon footprint and P to protein content and m to median. All quantities are given in g_{CO_2} eq./g protein. The average carbon intensity is calculated from the geometric average of the 4 previous columns, while the uncertainty range is given by the geometric average of the 2 first and 2 last columns.

Product	$\frac{C_{m,min}}{P_{max}}$	$\frac{C_{m,min}}{P_{min}}$	$\frac{C_{m,max}}{P_{max}}$	$\frac{C_{m,max}}{P_{min}}$	Average
Cow's	34	42	71	87	54 (38-79)
Goat's	27	34	137	168	68 (30-152)
Sheep's	31	65	81	171	73 (45-118)
Buffalo's	89	89	99	99	94 (89-99)

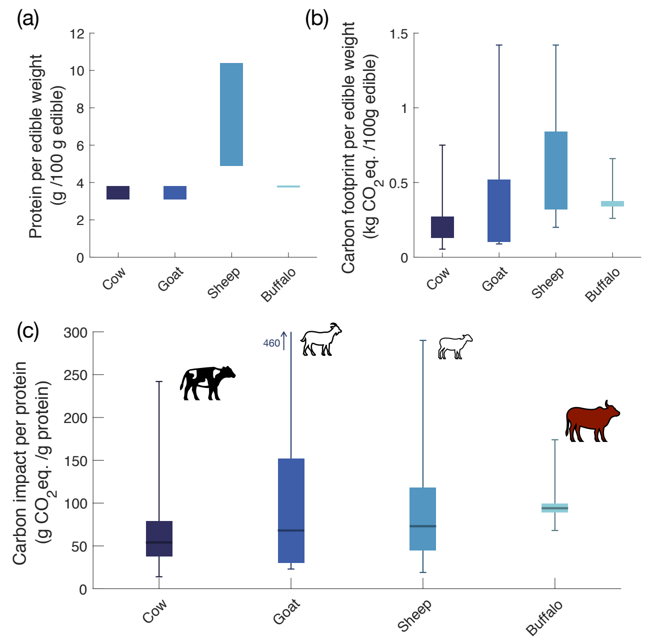

FIG. 5. Comparing the carbon footprint of various milks. (a) Protein content range retained in this study for 4 categories of milk. (b) Carbon footprint range and errors retained in this study for the milks. (c) Carbon impact per g of protein as calculated from (a) and (b), in a similar way as for Fig. **??**. Note that for Buffalo milk, available data is very limited.

In summary, cow's milk appears to be generally a little less carbon intensive per g of protein. In general milks from different species have a comparable carbon footprint per g of protein. Comparing milk from different species is only at its early stage. For example, LCA analysis of milk depends on a correction factor accounting for the typical quality of milk called the FPCM (fat and protein corrected milk). This factor corrects for milk quality between different farms – for example a farm may produce cow milk with a slightly higher protein ratio than another. It is well calibrated for cow and sheep but still under study for goat milk[78].

2. Different cheeses don't just taste different

Milk is the main primary component of dairy products, and dairy products are extremely varied, especially for cheese. Cheeses range from fresh cheese to hard cooked cheese, and all possible intermediate compositions. Because cheese preparations are so broad, the protein content of cheeses covers the broadest range of values: from $3-5g$ protein/100g for fresh yogurt, a few $10g$/100g for cream cheeses, common cheeses such as cheddar or mozzarella range between $15-25g$/100g and finally aged, very hard cheeses, such as parmesan, can hit up to $30g/100g$ – see Fig. 6 and Table X. However, cheeses with a higher protein content generally require more aging and thus have a larger carbon footprint[79]. It is thus natural to wonder whether the added carbon footprint is compensated by the higher protein content. To answer this question we investigate the carbon impact per g of protein for cheese.

We start by general considerations on the carbon impact of cheese. Raw milk production is the main component of a cheese's carbon footprint thus most carbon quantification efforts for cheese are focused on reducing the carbon footprint of milk produced for dairy plants[80,81]. In particular, the carbon footprint of cheese strongly depends on whether raw milk was produced on site, or transported – in its liquid or dehydrated state[80]. The second most significant contributor to the carbon footprint of cheese is processing[79]. Interestingly, industrial versus traditional techniques seem to perform quite as well carbon wise[82]. The aging part of processing is the most relevant part[80]. For example, Dalla et al.[83] compare the carbon cost of aging for two cheeses, ranging from 24 to 28g protein/100 g (edible) and find that carbon costs rise from 1.32 to 1.61 $kg_{CO_2,eq}$/kg (giving 5.5 to 5.7 $g_{CO_2,eq}$/ g protein). This hints to the fact that additional carbon costs may be well compensated by higher protein content.

This compensation effect is far from trivial. In fact, one could expect the carbon impact of proteins from cheese to simply increase concurrently with cheese aging. Yet Dalla et al.[83] example study shows that this is not the case. In fact cheese aging generates a number of co-products (whey, cream, butter, buttermilk etc) to which carbon is also allocated[79,84]. The carbon content of cheese (specifically aged cheese) is significantly dependent on what carbon weight is attributed to those co-products[84,85]. Even in the same plant, differentiating the carbon impact of two cheeses is quite difficult[79]. Cheese LCA is therefore quite subtle.

To investigate statistically whether higher protein content compensates for the carbon cost of aging, we gather data from a number of LCA – see Table X. We investigate a wide range of cheeses, and compare their carbon footprint per protein content in Fig. 6. We observe no clear trend in the data. This confirms that the carbon impact per g of protein of cheese does not depend significantly on the cheese's protein content. Therefore, in a consumer's low carbon perspective, choosing between different cheeses is not relevant.

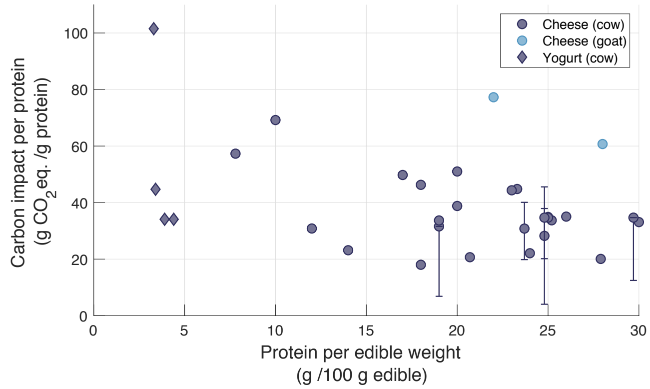

FIG. 6. Comparing the carbon footprint per g of protein of various dairy products, with a focus on cheese. The data is presented with respect to the protein content of the different dairy products. When confidence intervals were provided by the references investigated, they are reported in the graph.

3. Whey Powders for protein supplements

The dairy product with the largest protein content is whey protein concentrate, with 80-90g protein/100g[86]. For these products, data availability is extremely limited. Nonetheless, an extensive study allows to establish that whey concentrates emit 0.96 - 1.0 $g_{CO_2,eq}$/g protein[86]. Concentrated whey is therefore one of the least carbon impactful animal proteins. This is consistent with another study that shows that whey, per protein serving, is one of the least carbon impactful among different high protein options[87].

In contrast, standard whey products (not concentrated) – used for infant formula for instance – have similar carbon impact per g of protein as cheeses[79,86,88].

4. The carbon impact of butter

Analyzing different varieties of cheese highlights the critical role of co-products of the dairy industry in carbon impact assessment. Some of these co-products are particularly concentrated, not in protein, but in fat, such as butter (and other creams and oily preparations). Worldwide consumption of these products can not be disregarded. For example, in 2014, the worldwide average butter consumption was 700g/capita/year[77] (obviously ranging to much higher/lower values in specific countries). With a carbon footprint of 11.52 $kg_{CO_2,eq}$/kg in average[?] , this makes up about 8 $kg_{CO_2,eq}$/capita/year for butter consumption. To put this number in perspective, with 8 $kg_{CO_2,eq}$/capita/year, one could alternatively get 11-22 servings of chicken or 1-3 servings of beef (100g steaks, see Table VI).

Butter is one of the most carbon intensive sources of fat per kg[2,39]. Therefore, butter may very well be the high-fat product with the highest carbon footprint per g of fat. This sets the question of what are the best products (carbon wise) to obtain fat? An analysis similar to our analysis on proteins, this time comparing products with respect to their carbon footprint per g of fat, could be done to answer this question – yet is beyond the scope of the current study.

IV. CARBON IMPACT OF DIFFERENT DIETS CONTAINING MEAT AND DAIRY

We now turn to investigate how dietary choices may affect the carbon footprint of an individual. In fact, when discussing carbon footprint of the food supply chain, improvements in crop and breeding techniques seem to be insufficient to achieve carbon footprint targets[3,4,89]. Dietary changes have to be considered to meet this goal. There are many potential dietary choices and numerous authors have investigated the potential positive impact of alternative diets on carbon emissions[2,3,5,89–99]. A detailed investigation of different dietary choices and their carbon footprint is beyond the scope of this study. Instead, we keep a focus on animal proteins from meat and dairy, and investigate *among* these food categories, the carbon footprint of specific choices. First, we consider alternative diets starting from a reference diet (that of the average European) – see Sec. IV A. Then we explore how these dietary choices are more or less effective on carbon footprint reduction starting from different reference diets across the world – see Sec. IV B. Finally we discuss nutrition aspects of these alternative diets – see Sec. IV C.

A. Impact of specific dietary changes: example based on the European average diet

We start by investigating in detail the carbon impact of specific dietary choices on a representative diet, the average European diet. Table III recapitulates meat and dairy consumption in average in Europe. We base our calculations on the data and methodology presented in previous sections. The total protein intake coming from meat and dairy is 62.8 g/person/day[100]. The carbon footprint of the diet is 1328 kg_{CO_2} eq/year[101]. Note that product consumption and protein intake are not the ones *actually* ingested by consumers but are overestimated. These numbers do not include food losses at the final stages of the food chain, as discussed earlier[9]. However, they do correspond to the food that was actually needed for consumption and therefore are the correct amounts to calculate carbon impact on.

We now proceed to explore different diets. Our rule of work is to keep the total intake of animal protein constant across diets. Furthermore we only allow for food items within the initial categories. Our rules are designed to mimic easy swaps for a consumer choosing between food items, and minimal change of diet overall. Within these rules, we investigate 3 alternative diets: (1) a vegetarian diet consisting of dairy and eggs only (ovo-lacto-vegetarian), (2) a low carbon diet containing products that have a low carbon footprint with respect to protein intake, namely chicken, yogurt and eggs, termed "Low CO_2" henceforth, (3) and finally the diet with the lowest possible carbon footprint within these rules, containing only "Chicken".

TABLE III. Carbon impact and protein intake from meat and dairy consumption for a reference **European** diet, and resulting carbon impact for alternative diets keeping the same total number of proteins from meat and dairy. The product consumptions are all given in g/person/day. The vegetarian diet corresponds here to an ovo-lacto-vegetarian diet.

Product	Reference	Vegetarian	Low CO_2	Chicken
Pork	97.3[102]	0	0	0
Chicken	64.7[102]	0	196.5	313.2
Beef	29.6[102]	0	0	0
Lamb	3.8[102]	0	0	0
Milk	178.1[103]	437.8	0	0
Cheese	50.4[103]	123.9	0	0
Yogurt	50.7[104a]	124.7	154.2	0
Eggs	34.2[109]	84.1	103.9	0
Diet factor	1	2.5	3.0	4.8
Total protein[b]	65.8	65.8	65.8	65.8
Carbon impact[c]	**1319**	**1078**	**633**	**598**

[a] taken as the production of fermented products in EU27, 2013; Production of fermented products corresponds well with consumption of yogurt as seen with cross references to other countries[105–107]; dairy consumption evolution is smooth with time in Europe[108].
[b] calculated, g/day
[c] calculated, kg_{CO_2} eq/year

The amount of the different food items for each specific diet was adjusted such that the relative amounts of the food items are consistent with the relative amounts in the reference diet. Once again, this rule is designed to investigate alternative diets that are as close as possible to actual diets. Accordingly, for each food item, consumption has to be multiplied by a diet factor to meet the goal of conserved total protein intake. For example, in the vegetarian diet, the diet factor is 2.5, meaning that an individual would have to ingest 2.5 times more dairy and eggs than average and cut out all meat sources.

The resulting intake of different food items and the corresponding carbon impact of the different diets is reported in Table III and illustrated in Fig. 7. We observe that the carbon impact of the vegetarian diet is only 20% lower than the reference diet. This is due to the fact that the vegetarian diet still heavily relies on dairy products. Dairy originates from ruminants and is thus quite impactful carbon wise. Comparatively, the low CO_2 diet achieves a 50% reduction in the carbon footprint. This is interesting because it highlights that – within the rules defined in this study – a vegetarian diet may not be quite as effective as other diets including meat to reduce carbon footprint. Note that here, our low CO_2 diet includes chicken, but that could also work with any kind of poultry.

The chicken only diet achieves a marginal improvement compared to the low CO_2 diet as the low CO_2 diet is already quite abundant in chicken.

The improvement in carbon impact of diets when shifting from meat and dairy products to poultry was also noted by other works investigating complete or partial diet alternatives[4,91,93,95,98,110]. Dairy rich diets, or diets replacing meat by dairy products are in general not found to yield significant improvement of the carbon impact of the diet[91,93]. Comparing products solely based on their protein content fails however to take into account the benefits of specific micronutrients that can be found in these products[92]. This could slightly shift the balance, and we discuss these facts in more detail in Sec. IV C.

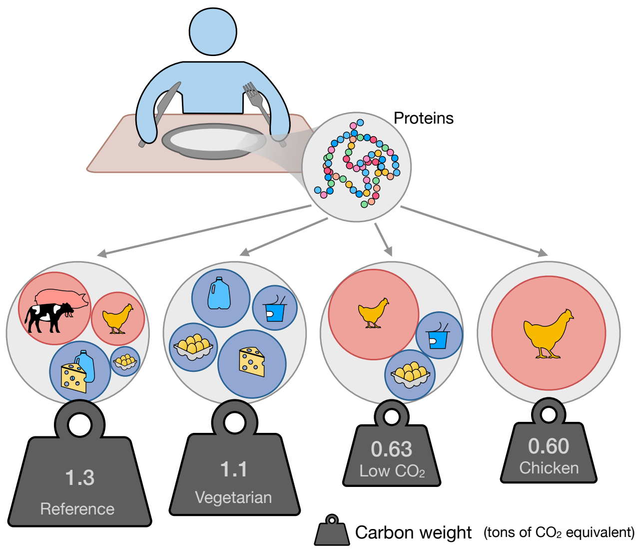

FIG. 7. Carbon footprint of different dietary choices starting from a reference European diet. The plates show 4 different diets (reference, vegetarian (with eggs and dairy only), low CO_2, chicken) with disks representing proportional contributions of the various animal proteins to the diets. The carbon weights attached to each plate also have areas proportional to the relative carbon footprints.

B. Impact of specific dietary changes across countries

Next, we explore how the efficiency of these alternative diets translates for representative populations across the world. This is quite relevant since carbon footprint reduction when switching diets is dependent on location[4]. Here, we investigated dietary changes for populations in the United States, in Brazil, in China and in India. The exact same methodology as for the European diet was applied for these different countries, and the results are reported in detail in Appendix E.

The choice of countries is purposely done to illustrate the diversity of dietary behaviors. For example, in average, in these countries the protein intake from meat and dairy is very diverse (see Fig. 8-a), ranging from 80 g/day/capita in the U.S.A. to barely 10 g/day/capita in India. However, the average carbon footprint per g of protein for these different countries is quite similar (see Fig. 8-b). The Brazilian diet (quite rich in meat and especially in beef) achieves the highest carbon footprint per g of protein. The chinese and indian diets (with quite high amounts of chicken for the chinese diet, and nearly vegetarian for the average indian diet), achieve the lowest carbon footprint per g of protein, but only about 30 % better than the Brazilian diet.

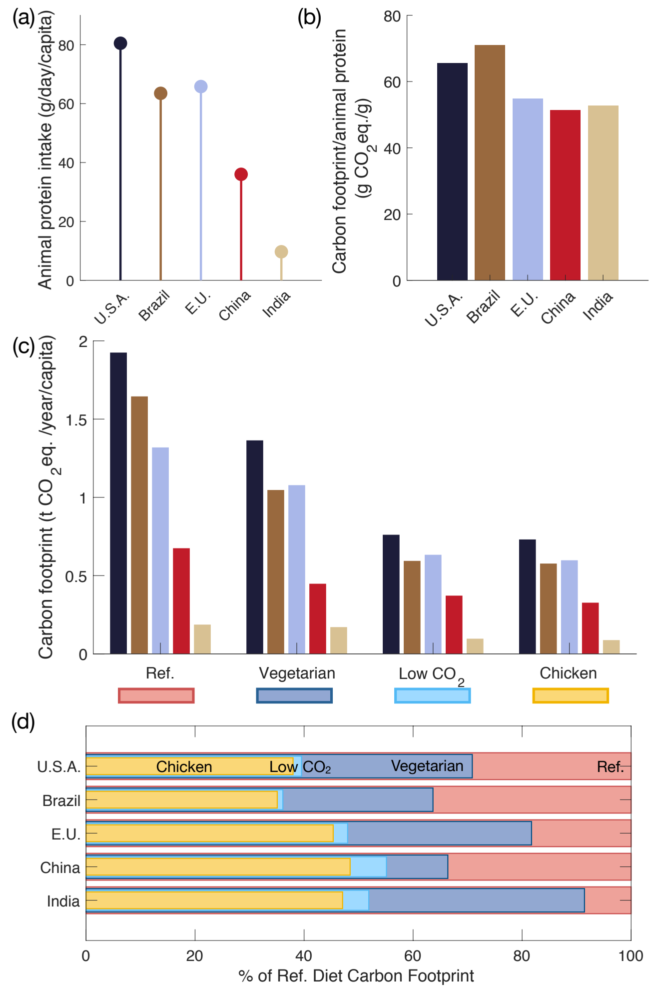

FIG. 8. Carbon footprint reduction for different dietary choices in different countries. (a) Daily animal protein intake for 5 chosen countries [a]; (b) Average carbon footprint per animal protein; (c) Yearly carbon footprint of the 4 different diets investigated in Fig. 7 for the 5 chosen countries; (d) Relative carbon footprint reduction for the different diets investigated for the 5 countries.

[a] from meat and dairy, excluding complementary protein intake in the form of *e.g.* protein powder

The switch to a vegetarian diet is especially effective (achieving over 30 % carbon footprint reduction) for the Brazilian and Chinese reference diets – see Fig. 8-c and d. Indeed, beef is a predominant component of the Brazilian diet. Therefore any alternative diet without beef achieves much better than the reference diet. For the Chinese diet, the analysis is different. The vegetarian Chinese diet contains quite low amounts of dairy but high amounts of eggs. Eggs are quite low in carbon impact per g of protein compared to dairy products. The vegetarian Chinese diet therefore resembles the "Low CO_2" diet. Comparatively, the switch to a vegetarian diet in India is quite ineffective as the initial average diet is already nearly vegetarian.

The switch to a "low CO_2" or "chicken only" diet is quite effective for all countries, allowing carbon footprint reductions from 45 to 65 %. These dietary changes are especially effective for the American and Brazilian diets as their initial consumption of beef is relatively high compared to other countries. In the Chinese and Indian diets, the switch from low CO_2 to chicken only diets is significant, reaching up to 5 % reduction. Indeed both low CO_2 diets contain large amounts of products with a higher carbon impact than chicken. The Indian low CO_2 diet is rich in yogurt and eggs, and the Chinese low CO_2 diet is rich in eggs. Overall this demonstrates that a shift to the low CO_2 diet has already a drastic impact over the carbon footprint of meat and dairy proteins.

C. A nutrition-oriented note on dietary changes

Beyond protein intake, other nutritional aspects should be considered when considering alternative diets[92,96,98]. This is a difficult task, as dietary reference points, *i.e.* most current average diets, are not necessarily nutritionally complete[94]. That being said, we still review some of the main nutritional challenges of the diets considered here.

To start with, all the diets investigated, including the reference diets, fail to reach adequate amounts for several nutrients, in particular for iron[111]. Lack of iron is consistently seen in another study investigating micronutrients of a complete average diet[94]. Furthermore, the chicken-only diet – or other alternative diets that do not include dairy – does not provide calcium, coming from dairy in the other diets[92]. This highlights that to achieve a healthy (*i.e.* nutritionally complete diet), additional food items should be carefully added to the diet. For dairy-light diets or chicken-only diets, calcium can be found in sufficient amounts with moderate dietary adaptation, for example by consuming more of certain vegetables, fruits or legumes (*e.g.* 3 cups of chopped kale bring as much calcium as 1 cup of milk – about 1/3 of the recommended daily allowance)[96,112]. Larger dietary shifts require more careful nutritional adaptations[96].

The non-reduction of animal protein throughout the alternative diets investigated here is a common downside. Yet, reduction of animal protein intake leads to a number of potential health benefits[95]. For example, the reduction of livestock product consumption by 30 % was projected to decrease the risk of ischaemic heart disease by 15 %[5]. This fact was corroborated by other studies[110]. Moreover, animal protein intake leads to higher blood serum levels of the hormone insulin-like growth factor 1 (IGF-1)[113]. These higher levels are important risk factors in several types of cancer[114,115] (prostate[116,117]; colorectal[110], and breast cancer[118] for example). Furthermore, trading animal proteins for plant-based proteins in a diet comes with a great reduction in carbon footprint[2,39]. Plant-based proteins are therefore promising sustainable foods – though comparing their carbon footprint to that of animal proteins is beyond the scope of this study.

All these arguments point to the fact that beyond their content in protein, or in calories, foods should also be compared for their content in micronutrients. For example, the carbon score of dairy could be improved because it does bring important quantities of calcium[92]; similarly pork contains more micronutrients than chicken[94]. Such scoring for diets is still at its early stages and alternative diets – especially vegan diets – should be carefully balanced to fulfill micronutrient targets (Note that a healthy vegan diet reaching all micronutrient targets is possible in developed countries[72,119] but some studies fail to compare diets where all micronutrient targets are reached[92]). Alternatively, whereas numerous discussions are focused on what micronutrient targets some alternative diets do *not* fulfill; little discussion and scoring is performed on *excessive* micronutrient intake, or potentially long-term disease associated with some foods[119]. For example, although dairy is potentially interesting for its high level in calcium, high dairy intake may be associated with higher risk in prostate cancer[120] via IGF-1[117]. This is not the case for non-dairy calcium sources. A detailed investigation of micronutrient targets can thus only be performed within entire diet compositions, and with careful set up of scoring measures.

V. CONCLUSION AND OUTLOOK

In summary, we have introduced a methodology to compare the carbon footprint of protein rich foods, in particular of meat and dairy protein. Our results show that ruminant meat and dairy have a high carbon footprint per g of protein; while other meats (such as pig and poultry) and protein-rich dairy (such as yogurt) have a quite lower carbon footprint. We have made our data readily available for consumer use through an online application[57]. Furthermore, we have investigated several consumer-oriented questions; such as choosing between local or imported, organic or non-organic, and within the variety of dairy products. These investigations point to a general poor data availability, showing that consumer-oriented questions are hard to answer at this stage. More life cycle analysis and meta data treatment with a consumer perspective could be done.

We have studied the impact of dietary changes within the meat and dairy food categories. Our analysis relies on the assumption that the consumer does not change its total protein intake from meat and dairy. Interestingly, a change to ovo-lacto-vegetarian diet results in a low improvement of the carbon footprint; while a change to poultry, yogurt, and eggs diet results in a drastic, 50 %, improvement. This is quite comparable to the IPCC target[1]. However, the low carbon diet would not be sufficient to reach the target since such drastic improvements in food emissions can not necessarily be obtained over all food sources[39]. Alternative food sources, and in particular alternative protein sources (plant-based or from fish), should be investigated and compared in similar ways to offer consumer-friendly perspectives. This is the aim of future work. Furthermore, although our study was focused solely on carbon footprint, meat consumption, and in particular red meat consumption, has a high environmental impact with respect to water, pesticide and fertilizer usage, ocean acidification, toxic emissions in the air and land eutrophication[45,72,75,76,121,122].

As outlined in the nutritional discussion in Sec. IV C, our study investigates solely the carbon impact with respect to protein content and does not account for other nutritional aspects. Beyond micronutrient targets, and as highlighted by a number of authors, many other factors come into play. For example when comparing protein rich foods it has been noted that not all protein sources are equivalent because some are easier to digest[87,123]. Furthermore, factors such as geographical dependencies of carbon footprint[97], cost of the alternative diet[96,97] and cultural adequacy[96] are very relevant points to address when considering alternative diets. These factors require careful introduction of scoring measures, and all participate in understanding how to best achieve the IPCC target.

ACKNOWLEDGEMENTS

The authors are indebted to Amaury Hayat and William Legrand for sparking interest in the topic.

APPENDICES

Appendix A: protein content of meat and dairy retained for this study

A.1. Measuring the protein content of meat

After meat has been cleared from bones – sometimes trimmed from fat – the amount of pure nitrogen contained is measured using a number of chemical reactions. A conversion factor is then used to relate the pure nitrogen content and the nitrogen contained originally in proteins in the food (purple circle in the amino acids of Fig. 2)[35]. This allows to quantify the protein content of the food. The conversion factor most widely used today, in particular used to calculate the data we report below, relies on an early study[38]. However, it is to be noted that this conversion factor is an early estimate that does not properly take into account the various nitrogen contents of proteins[124] and a different factor is strongly recommended by scientists today[125]. To ensure consistency of our study, we will still use data resulting from the older factor, noting that the difference between the two factors is only 20% and does not vary much among the food categories investigated.

Protein content data has a lot of variability. For example, the breeding methods used change with time and affect the protein content[35]. But also the breed itself and the sex of the animal[126]. Moreover, ready-to-eat meat comes from different parts of the animal that do not have the same content in water and fat and therefore the content in protein differs (such as sausage for which the fat content is higher in average, and therefore less dense in protein than trimmed steak). Finally, extrinsic properties caused by manufacturing and processing affect the protein content[35,126]. All of these factors also affect what is said to be the "meat quality". Meat quality is a measure of the different kinds of amino acids (coming from proteins) that can be found in the meat and how they are ingested and properly used by our organism[10,28,126]. To lessen such variability, here we discard processed foods such as patties, sausages, and other prepared meals.

A.2. Protein content of meat and dairy products investigated in this study

We report here values of proteins found in meat and dairy products from various national databases[10,35–37]. Protein content of common meat-based products may be found in Table IV and of dairy products in Table V. In each table; the protein content range is the minimum to maximum of protein content that we have retained. This accounts for the variability mentioned in Appendix A.1.

A.3. How much protein comes from meat in diets ?

To put these numbers in perspective, let's take an example corresponding to a plausible meat consumption. Let's assume a dietary reference intake of 1 g/kg.day of protein (as discussed in the Introduction). We require it to be covered at 50 % with meat. From Table IV, we can take a rough value of the protein content of meat around 20 g of protein/100 g of meat. This means that a person weighing 60 kg (132 lbs), respectively 80 kg (176 lbs), would need to eat 150 g, respectively 200 g, of meat per day. This matches well with the average meat consumption in several countries[8].

Appendix B: carbon footprint of meat and dairy retained for this study

B.1. Carbon impact of meat and dairy products

To assess the carbon impact of meat and dairy products, we gather data from various sources[2,39,41,42] – each of which are either peer-reviewed data or data gathered by national agencies. We require that these sources contain sufficient information on the methodologies. These are Life Cycle Analysis (LCA) averaged over a national scale or meta-analysis of LCAs that concern worldwide distributed plants/farms.

The LCAs retained share the same functional units (1kg of edible meat and most dairy products, 1kg of Fat and Protein Corrected Milk for milk). The boundaries of the LCAs retained for this study are from cradle to farm-gate[42,129], or beyond. To be more specific they extend to Regional Distribution Centre[39], to retail[2] or (for just a few) to grave[41]). Transport and other processing costs beyond the farm-gate stage for the products considered here (meat and dairy) represent only a small fraction of the cost from cradle to farm-gate[62] (in median only 77 $g_{CO_2}eq./100g$ edible[39]). For products such as fresh vegetables, these costs are more relevant[62]. In fact, such difference lies within the uncertainty range. For example, median calculations from cradle to farm-gate[42] show for a few products slightly *more* important carbon impacts than more complete assessments from *e.g.* cradle to Regional Distribution Centre[39] – potentially due to particular methodological differences in LCA assessment, that are beyond the scope of our work. Therefore, in an effort to assess the carbon footprint of the most possible products, we conserve all data with boundaries at least between cradle to farm-gate. This process can add more extreme carbon footprint values. To avoid distorting the data calculated on carbon footprint per g of protein, we will resort to specific data management choices, such as the use of geometric averages – see Appendix C.1.

B.2. Carbon impact of meat and dairy products investigated in this study

We report here values of carbon impact for the production per gram of meat and dairy products from various databases[2,39,41,42,55,79,129–132]. Carbon impact per 100 g of edible food of common meat-based products may be found in the Appendix B in Table VI and of dairy products in Table VII. In each table, we highlight the carbon footprint range that we have retained. Unless data is not available, minimum and maximum median values are taken from world averaged, meta-analysis such as 2, 39, and 40 while other extreme values are taken from the reported extreme values of 2 and 39 or national averages[41,42].

Appendix C: Calculating carbon footprint per g of protein

C.1. Use of geometric averages

To present the data, we use geometric averages instead of arithmetic averages for three main reasons [43,44,139]:

- We are averaging ratios and the geometric mean treats the numerator and denominator equally.
- The uncertainty for all the values are rather high (most probably higher than 10%). With an arithmetic mean, a fixed percentage error (say 10%) made on the maximum values would be amplified much more than on the minimum values as they often have different orders of magnitude.
- Our data is likely to be skewed in some way. Even with all the meta-analyses considered the probability is high that for the same product one might find a sample with higher (resp. lower) values (be it carbon intensity or protein content) than the maximum (resp. minimum) values presented here.

C.2. Extreme values for carbon impact per g of protein of meat and dairy products

We present in Tables. VIII and IX extreme values of carbon footprint per g of protein as calculated using the extreme retained values of carbon footprint in Appendix B.2.

Appendix D: carbon impact per g of protein of different type of cheeses

We present in Table X the protein based carbon intensity of different cheeses and in Table XI of more varied dairy products.

Appendix E: typical dietary intakes and comparison of carbon impact of different diets equivalent in protein

We present in Tables XII-XV the carbon impact and protein intake from meat and dairy consumption for reference and alternative diets for various countries.

TABLE IV. Protein Content of common meat-based products. All of the data reported is given without bones[35], and for raw meat.

Protein Content of common meat-based products		
Meat-based product	Protein content range (g/100g raw)	List of references used
Beef	17.1-24.9	*Trimmed parts* (lean) 22.5[35], (fat) 18.9 [35] (minced) 19.7[35], (rumsteack) 20.7[35] (loin) 22.2-24.9[36] (round) 23.4-23.7[36], (all) 18.4-24.1[10]; *Ribs* 18.8[35]; *Stewing steak* 22.1[35], 21.2-24[10]; *burgers* 17.1[35], (lean and not) 17.3-21.9[10]
Veal	16.7-22.7 [a]	*Scallops* 20.7[10], 22.7[35]; *burgers* 16.7-17.2[10]; *other* 18.3-27.3[10], 16.95-20.92[37]
Pork	15.8-22.7 [b]	*Bacon* 16.5[35], 15.8[35], 17[10]; *ham* (salami) 18.4[35], 17.4[35] (ham, 4% fat) 20.9[35] (cooked) 15.1-18.1[36], 18-21.6[10] (uncured) 24.2-30.4[10]; *trimmed* 18.6-21.8[35] 15.9-22.7[10]; *sausages* 11.9-13.6[35], 11.8-17.3[10]
Chicken	18.4-24 [c]	*Dark meat, such as thighs* 20.9-24.0[35]; *Dark and white* 18.4-23.5[10];*roasting, meat only* 20.44[37]; *ground* 17.04-17.93[37]; *broilers or fryers, variable content of skin* 17.88- 22.2[37]
Turkey	19.8-24.4 [c]	*Dark meat, such as thighs* 24.4[35], 20.6, 21.28[37]; *White meat, such as breasts and wings* 20.4[35], 21.28[37], 20.22[37]; *Dark and white* 19.8-23.4[10]; *Sausage* 18.79[37]; *Ground* 19.66[37]; *other* 15.6-19.7[36], 18.79[37]
Lamb	16.3-20.3	*Loin chops, cutlets* 16.3[35], 17.6[35]; *trimmed, minced* 20.2[35], 19.1[35]; *shoulder* 17.6[35], 17.5-20[10]; *other* 20.3[37]
Duck	17.4-19.9	19.7[35], 17.4-19.4[10], 18.28-19.85[37]
Rabbit	20.1-21.9	21.9[35], 20.4-21.8[10], 20.05[37]
Game meat [d]	*20.7 - 23.7*	*deer, roe, pheasant, boar, rabbit* 20.7-23.7[10]; *bison, deer, boar, rabbit* 21.51, 21.62, 21.79, 22.96[37]
Ostrich [d]	*20.2 - 23.7*	20.2[10] 20.22-23.69[37]
Organ meats [d,e]	*7.1 - 21.8*	*Pork* 7.1[35], 12.1[10] *Beef* 10.3-21.8[10]

[a] keeping only scallops and burgers to keep only well-identified parts
[b] Removing sausages and ham that differ greatly according to the kind of preparation involved
[c] Removing not well identified parts, and sausages and ground meat that differ greatly in preparation
[d] For these products, little or no data on carbon footprint was found. Especially for game meat, where the footprint is very limited since animals are not tended. We elaborate on game meat in the discussion section.
[e] This corresponds to various organ meats such as liver, tongue, etc.

TABLE V. Protein Content of common dairy products; As an indicative note, a typical egg weighs between 40 and 70 grams[127], resulting in about 4-9 g of protein per egg.

Protein Content of common dairy products and eggs		
Dairy product	Protein content range (g/100g raw)	List of references used
Milk (cow, skimmed to whole)	3.1-3.8	3.3-3.4 (*average, UHT or pasteurized*)[35], 3.24-3.8[10], 3.06-4.02[36]
Milk (goat)	3.1-3.8	3.22-3.77[10] 3.1 (*average, UHT or pasteurized*)[35], 3.56[37]
Milk (sheep)	4.9-10.4	4.85-10.4[128] 5.4 (*average, raw*)[35], 5.98[37], 5.68[10]
Milk (Buffalo)	3.8	3.75[37]
Fresh cheese (cow)	7.7-13.3	12.6 (*cottage cheese*)[35], 7.65[10], 8.55-13.3[36]
Soft cheese (cow)	16.9-25.6	*Brie* 17.3-22[10] 20.3[35]; *camembert* 21.5[35], 21[10]; *blue cheeses* 20.5-23.7[35] 19.6[10]; *mozzarella* 18.6 [35], 16.9[10], 20.9-25.6[36]
Soft hard cheese (cow)	20.4-24.6	*Reblochon* 20.4 [10]; *saint-nectaire* 22.5[10]; *raclette* 24.6 [10]
Cooked cheese (cow)	21.5-36.2	*Cheddar* 24[10], 25.4[35], 21.5-25.6[36]; *parmesan* 34.1-34.5[10], 36.2[35], 34.1[10]; *comte and other related cooked cheeses* 27.1-28.4[10]; *swiss cheese* 25.7-28.3[36]
Fresh cheese (goat, sheep)	14.8-20.7	*Feta* 14.8[10] 15.6[35]; *other* 19.8-20.7[10]
yogurt (plain to low fat, cow)	4.1-5.7	4.12-4.82[10] 4.8-5.7[35], 5.25[37]
yogurt, greek style (low fat, cow)	6.9-12.2	7.95[10]-9.89[10] 6.89-12.2[36]
Eggs (chicken)	11.8-12.7	12.5[35], 11.8-12.7[36], 12.7[10]

TABLE VI. Carbon footprint data of meat products retained in this study. The range of carbon footprints for each product is made out of four numbers: the lowest single value, the lower median value, the higher median value, the highest single value found in meta-analyses or systematic reviews.

Carbon intensity for meat-based products		
Meat-based product	Carbon footprint range (g_{CO_2} eq./100g edible)[a]	List of references used
Beef	1074 – 2661-6040 – 26920	**2700**[41] (*Average, USA*); **3100**[129,133] (*Average, Canada*); **1074-10950 (2661±1247)** [b,39] (*meta-analysis*); **3760-26920 (6040)** [c,2] (*meta-analysis*); **2860 ± 30%**[42] (*Average, France*)
Veal	1148 – 1640-3859 – NA	**3859**[130–132] (*LCA with equal allocation for calves and grown beef*); **1640 ± 30%**[42] (*Average, France*)
Pork	320 – 577-1060 – 2380	**1210**[41] (*Average, USA*); **320-1186 (577±163)**[b,39] (*meta-analysis*); **690-2380 (1060)**[c,2] (*meta-analysis*); **589**[42] (*Average, France*)
Lamb	1005 – 2558-4060 – 6020	**3920**[41] (*Average, USA*); **1005-5670 (2558±1193)**[b,39] (*meta-analysis*); **2370-6020 (4060)**[c,2] (*meta-analysis, no distinction between Lamb and Mutton*); **3300± 30%**[42] (*Average, France*)
Chicken	106 – 365-750 – 2080	**690**[41] (*Average, USA*); **106-998 (365±172)**[b,39] (*meta-analysis*); **400-2080 (750)**[c,2] (*meta-analysis*); **475± 30%**[42] (*Average, France*)
Turkey	334 – 628-717 – 1090	**1090**[41] (*Average, USA*); **334-849 (717±66)**[b,39] (*meta-analysis*); **628± 30%**[42] (*Average, France*)
Duck	207 – 309-583 – 758	**207-410 (309±144)**[b,39] (*meta-analysis*); **583± 30%**[42] (*Average, France*)
Rabbit	382 – 470-486 – 558	**382-558 (470±124)**[b,39] (*meta-analysis*); **486± 30%**[42] (*Average, France*)

[a] The numbers are given as [Absolute min – $Median_{min}$-$Median_{max}$ – Absolute max]
[b] numbers indicate here: min-max (median ± standard deviation);
[c] numbers indicate here: 5th percentile-95th percentile (median);

TABLE VII. Carbon footprint data for dairy products retained in this study. The range of carbon footprints for each product is made out of four numbers: the lowest single value, the lower median value, the higher median value, the highest single value found in meta-analyses or systematic reviews. For Sheep, Goat and Buffalo Milk, data is generally less available and values generated by world or national scale LCA are highlighted in bold compared to more local analysis.

Carbon intensity for dairy products		
Dairy product	Carbon footprint range (g_{CO_2} eq./100g edible)[a]	List of references used
Cheese (Cow)	533 – 855-1860 – 5880	**1347**[41] (*Average, USA*); **533-1635 (855±207)** [b,39] (*meta-analysis*); **1020-5880 (1860)** [c,2] (*meta-analysis*)
Yogurt (Cow)	117 – 131-288 – 374	**217**[41] (*Average, USA*); **117-200 (131±25)**[b,39] (*meta-analysis*); **288 ± 30%**[42] (*Average, France*)
Milk (Cow)	54 – 129-270 – 750	**54-750 (129±58)**[b,39] (*systematic review*); **150-700 (270)**[c,2] (*meta-analysis*); **122 ± 30%**[42] (*Average, France*; **106-123**[45] (*Table 59, non-organic–organic, Average, England and Wales*)
Milk (Sheep)	160 – 320-840 – 1420	**160-1420 (840)**[d,134] (*world average, variation of footprint corresponds to varying yields across the world, cradle to retail*); 200-520 (320) [d,135] (*12 farms, variation of footprint corresponds to varying yields in different farms, cradle to farm-gate LCA*);
Milk (Goat)	89 – 104-520 –1420	**104-140**[78] (*16 representative farms, cow's milk FPCM correction factor retained to be consistent with other studies, variation of footprint corresponds to varying allocation scenarios, cradle to farm-gate LCA*); , 112-505 (267)[d,136] (*17 farms, variation of footprint corresponds to varying yields in different farms, cradle to farm-gate LCA*); **160-1420 (520)**[d,134] (*world average, variation of footprint corresponds to varying yields across the world, cradle to retail*); 81-103 (89)[d,137] (*5 farms, variation of footprint corresponds to varying yields in different farms, cradle to farm-gate LCA*);
Milk (Buffalo)	260 – 340-375 – 660	**260-660 (340)**[134] (*world average, variation of footprint corresponds to varying yields across the world, cradle to retail*); 287 – **360-375** – 520[e138] (*6 farms, cradle to farm-gate LCA*);
Eggs (chicken)	130 – 346-420 – 850	**483**[41] (*Average, USA*); **130-600 (346±121)**[b,39] (*meta-analysis*); **290-850 (420)**[c,2] (*meta-analysis*); **209**[42] (*Average, France*); **525-700**[45] (*Table 58, 100% cage non-organic-organic, egg weight 50 g, Average, England and Wales*);

[a] The numbers are given as [Absolute min – $\text{Median}_{\text{min}}$-$\text{Median}_{\text{max}}$ – Absolute max] or as [Absolute min – Median – Absolute max] or as [Median] when no more detailed information could be found

[b] numbers indicate here: min-max (median ± standard deviation);

[c] numbers indicate here: 5th percentile-95th percentile (median);

[d] numbers indicate here: min-max (average);

[e] Numbers indicate here (farm min - average for different allocation scenarios - farm max)

TABLE VIII. Protein based carbon intensity: extreme values.

Meat-based/dairy product	Protein based carbon intensity: extreme values		
	C_{min} / $Protein_{max}$ (g_{CO_2} eq./g protein)	C_{max} / $Protein_{min}$ (g_{CO_2} eq./g protein)	Geometric average carbon intensity (g_{CO_2} eq./g protein)
Beef	43	1574	194
Lamb	50	369	177
Veal	51	NA	129
Milk	14	242	54
Cheese	15	348	51
Pork	14	150	41
Turkey	15	55	32
Eggs	10	72	31
Yogurt	10	91	27
Chicken	4	113	25
Rabbit	17	28	23
Duck	10	44	23

TABLE IX. Protein based carbon intensity for milks: extreme values.

Milk product	Protein based carbon intensity: extreme values		
	C_{min} / $Protein_{max}$ (g_{CO_2} eq./g protein)	C_{max} / $Protein_{min}$ (g_{CO_2} eq./g protein)	Geometric average carbon intensity (g_{CO_2} eq./g protein)
Cow's	14	242	54
Goat's	23	458	68
Sheep's	19	290	73
Buffalo's	68	174	94

TABLE X. Protein based carbon intensity of different cheeses (starting from cow's milk, unless otherwise mentioned). The carbon intensity reference contains in general a reference of the protein content of the cheese investigated. When the protein content of the cheese is not found in the reference for carbon, it is usually a specific cheese whose protein content may be found elsewhere, in which case the reference is given.

Protein based carbon intensity of different types of cheeses				
Type of cheese	P (g protein/100g)	C (g_{CO_2} eq./100g)	C/P (g_{CO_2} eq./g protein)	Notes
Yellow cheese low fat	30	993[140]	33	
Grana Padano	29.7	1030 (max with diff. allocations 1690)[141]	35 (max 57)	hard cooked, dry matter allocation as central value
Pecorino artisanal	28	1700[82]	61	goat cheese, hard cooked
Emmental	27.9[10]	560[42]	20	hard cooked
Yellow cheese	26	911[140]	35	
Dutch Cheese	25.2	850[142]	34	semi-hard
Hushallsost	25[143]	873[144]	35	
Gouda	25[37]	867[145]	35	
Cheddar	24.8	700 (range with diff. allocations 460-1300)[88]	28 (19-52)	Semi-hard, economic allocation as central value
Cheddar	24.8	860 (range with diff. allocations 590-1220)[79]	35 (24-49)	Semi-hard, economic allocation as central value
Cheese (generic)	24	530[34]	22	canadian meta-analysis
Mozzarella	23.7[36]	730 (range with diff. allocations 510-990)[79]	31 (22-42)	semi-hard, protein content may vary significantly
San Simon da Costa	23.3[146]	1044[147]	45	
Casin (hard) artisanal	23[148]	1020[55]	44	
Pecorino (industrial)	22	1700[82]	77	goat cheese, hard cooked
Camembert	20.7[10]	428[42]	21	
Soft cheese	20	776[149]	39	meta-analysis
Franxon (artisanal)	20[150]	1020[55]	51	semi-hard
Gorgonzola	19	600 (max with diff. allocations 1070)[151]	32 (max 56)	hard cooked, dry matter allocation as central value
Cheese	19	640[86]	34	semi-hard to hard, meta-analysis
Fresh cheese	18[149]	324	18	meta-analysis
White cheese	18	833[140]	46	
Mould cheese	17	846[140]	50	
Cottage cheese	14	324[34]	18	canadian meta-analysis
Cottage cheese	12	370[140]	31	
Cream cheese	10	692[140]	69	
Cream cheese low fat	7.8	447[140]	57	

TABLE XI. Protein based carbon intensity of different dairy products (starting from cow's milk, unless otherwise mentioned). The carbon intensity reference contains a reference of the protein content of the product investigated.

Protein based carbon intensity of different types of dairy products				
Type of product	P (g protein/100g)	C (g_{CO_2} eq./100g)	C/P (g_{CO_2} eq./g protein)	Notes
Yogurt	4.4	150[34]	34	canadian meta-analysis
Yogurt low fat	3.9	133[140]	34	
Yogurt	3.4	152[140]	45	
Yogurt	3.3	335[149]	102	meta-analysis
Whey protein concentrate (special)	90	17360[140]	193	
Whey protein concentrate	80	16400[140]	205	
Whey powder	30	1010[34]	34	canadian meta-analysis
Whey powder	25	740[86]	30	meta-analysis

TABLE XII. Carbon impact and protein intake from meat and dairy consumption for a reference **American** diet, and resulting carbon impact for alternative diets keeping the same total number of proteins from meat and dairy. The product consumptions are all given in g/person/day.

Product	Reference	Vegetarian	Low CO_2	Chicken
Pork	63.0[102]	0	0	0
Chicken	136.2[102]	0	315.6	382.9
Beef	71.5[102]	0	0	0
Lamb	1.4[102]	0	0	0
Milk	181.4[107]	587.7	0	0
Cheese	49.7[107]	161.1	0	0
Yogurt	16.6[107]	53.9	38.6	0
Eggs	39.3[152]	127.4	91.2	0
Diet factor	1	3.2	2.3	2.8
Total protein[a]	80.5	80.5	80.5	80.5
Carbon impact[b]	**1 925**	**1 364**	**761**	**731**

[a] calculated, g/day
[b] calculated, kg_{CO_2} eq/year

TABLE XIII. Carbon impact and protein intake from meat and dairy consumption for a reference **Chinese** diet, and resulting carbon impact for alternative diets keeping the same total number of proteins from meat and dairy. The product consumptions are all given in g/person/day.

Product	Reference	Vegetarian	Low CO_2	Chicken
Pork	83.3[102]	0	0	0
Chicken	31.8[102]	0	75.8	171.3
Beef	10.4[102]	0	0	0
Lamb	8.5[102]	0	0	0
Milk	39.2[153]	144.2	0	0
Cheese	0.1[153]	0.2	0	0
Yogurt	9.4[153]	34.6	22.4	0
Eggs	62.7[154]	230.9	149.6	0
Diet factor	1	3.7	2.4	5.4
Total protein[a]	36.0	36.0	36.0	36.0
Carbon impact[b]	**675**	**448**	**372**	**327**

[a] calculated, g/day
[b] calculated, kg_{CO_2} eq/year

TABLE XIV. Carbon impact and protein intake from meat and dairy consumption for a reference **Brazilian** diet, and resulting carbon impact for alternative diets keeping the same total number of proteins from meat and dairy. The product consumptions are all given in g/person/day.

Product	Reference	Vegetarian	Low CO_2	Chicken
Pork	63.0[102]	0	0	0
Chicken	110.4[102]	0	255.6	302.2
Beef	69.0[102]	0	0	0
Lamb	1.4[102]	0	0	0
Milk	132.1[155]	610.5	0	0
Cheese	19.7[155]	91.2	0	0
Yogurt	21.2[155]	97.9	49.0	0
Eggs	21.3[109]	98.4	49.3	0
Diet factor	1	4.6	2.3	2.7
Total protein[a]	63.5	63.5	63.5	63.5
Carbon impact[b]	**1645**	**1047**	**594**	**577**

[a] calculated, g/day
[b] calculated, kg_{CO_2} eq/year

TABLE XV. Carbon impact and protein intake from meat and dairy consumption for a reference **Indian** diet, and resulting carbon impact for alternative diets keeping the same total number of proteins from meat and dairy. The product consumptions are all given in g/person/day.

Product	Reference	Vegetarian	Low CO_2	Chicken
Pork	0.5[102]	0	0	0
Chicken	6.6[102]	0	21.6	46.1
Beef	1.4[102]	0	0	0
Lamb	1.4[102]	0	0	0
Milk	129.9[155]	162.9	0	0
Cheese	6.6[155]	8.2	0	0
Yogurt	6.3[106]	7.9	20.7	0
Eggs	8.9[109]	11.2	29.2	0
Diet factor	1	1.3	3.3	7.0
Total protein[a]	9.7	9.7	9.7	9.7
Carbon impact[b]	**187**	**171**	**97**	**88**

[a] calculated, g/day
[b] calculated, kg_{CO_2} eq/year

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[49]Taking data from[52], Netherlands case, a cow produces about 4000 kg milk / year, for an average of 6.5 years, totalling to 26 tons of milk produced / cow. To simplify the argument, we discard calves in the balance. When a cow is slaughtered the carcass weight is about 300 kg, which amounts to about 190 kg of edible meat. That makes up 0.007 kg meat/kg of milk produced. (taking a 62% dressing factor and a 40% conversion factor from live weight to carcass weight[133]) In a dairy farm the average amount is actually a bit bigger (0.0025 kg meat/kg of milk) since the farms are mixed and also include at least as many beef as cows and approximately two calves are slaughtered during the cows life.

[50]Taking the result of 100/(858+38).

[51]p. c. e. Retail prices for beef, pork and dairy products last updated 4/10/2020, "U.s. department of agriculture (usda) – economic research service –," .

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