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

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A R T I C L E I N F O

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A B S T R A C T

Meat and dairy products in the food industry represent a significant portion of anthropogenic green house gas emissions. To meet the Intergovernmental Panel on Climate Change recommendations to limit global warming, these emissions should be reduced. 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 present a practical and pedagogical review, comparing the carbon footprint of a variety of meat and dairy products with respect to their protein content. We investigate the carbon footprint of different dietary choices for several countries, by keeping the total number of meat and dairy proteins constant. Interestingly, we find that dairy-only diets are in general only a little less carbon intensive than current diets. However, 50% carbon footprint reduction may be obtained, throughout the world, with a "low CO_2"-tailored diet including only small poultry, eggs and yogurt. Such a dietary pattern suggests easy to follow consumer guidelines for reduced carbon footprint. We report further on a number of consumer-oriented questions (local or imported? organic or not? cow or goat milk? hard or soft cheese?). 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.

1. 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 (Hoegh-Guldberg et al., 2018). To limit the increase of global average temperature compared to pre-industrial level, substantial efforts are needed. According to the Intergovernmental 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 (Hoegh-Guldberg et al., 2018) – 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 (Hoegh-Guldberg et al., 2018).

1.1. 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.) (Poore and Nemecek, 2018). That represents 26% of the total anthropogenic green-house gas (GHG) emissions (Poore and Nemecek, 2018) – see Fig. 1a. Furthermore, significant increase of food chain related emissions is expected with population increase and income level increase (Springmann et al., 2018). Therefore, in line with IPCC guidelines, reducing the emissions of the food supply chain is critical (Garnett, 2011; Friel et al., 2009; Springmann et al., 2018).

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 (Friel et al., 2009; Gerber et al., 2013; Springmann et al., 2016). More than half of the emissions from food stems from livestock because a number of 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 (Poore and Nemecek, 2018). Land use change (initial deforestation to create a pasture, and subsequent soil contamination) represents 27% (Poore and Nemecek, 2018) and animal feeding (growing crops to feed livestock) represents 3%. Transport, processing, packaging and retail fill up the remaining categories (about 4%) – see Fig. 1b.

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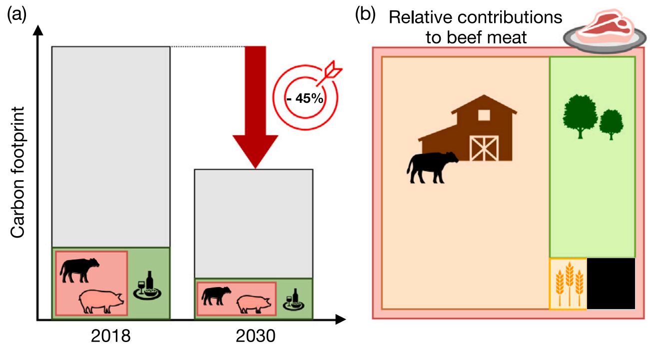

Fig. 1. (a) Proportion of food and livestock based products in the global carbon footprint balance of anthropogenic emissions and the relative change recommended by IPCC for the 2030 Target. The areas of the respective boxes correspond to the proportional carbon footprints of food production and livestock management. (b) Example of relative carbon footprint contributions for the production of beef meat: at the farm (orange), through land use change (green), feed production (yellow) and transport (black). Box areas correspond to relative carbon footprint contributions.

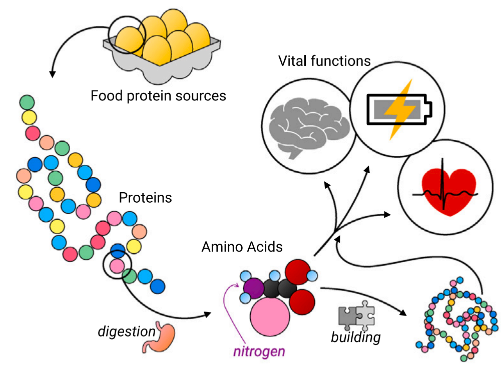

Fig. 2. Illustration of the cycle of proteins and amino acids in human nutrition and their use in several vital functions.

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 (stats, 2020a), corresponding to about 340 g of meat per day (not counting food losses at the consumer level).[1] This value falls to 210 g/day (stats, 2020a) in the European Union, 160 g/day in China and the world average is 115 g/day (stats, 2020a). Calorie wise, taking a typical number of 200 kcal/100g of meat (Agence nationale de sécurité sanitaire de l'alimentation, 2020), beef represents 8%–24% of total calorie intake (I. of Medicine, 2005).[2] 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 and represents on its own 36% of food-related emissions in the country (Heller and Keoleian, 2015).

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.

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

Proteins are large molecules made up of chains of amino acids. Briefly, digestion breaks them down into amino acids – see Fig. 2. Amino acids achieve vital functions — for example some are used for neurotransmission (Layman et al., 2015). Amino acids can be further broken down to produce energy to power our body (Sakami et al., 1963) (and the rest of the pieces – urea and carbon dioxide – are eliminated respectively by urine and breathing). Finally they can also be reassembled by the organism to synthesize other kinds of proteins that achieve a number of other vital functions in our body (Layman et al., 2015). In short, human life is impossible without proteins.

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 (I. of Medicine, 2005; de l'Anses, 2016).[3] Higher values of protein intake per day can be beneficial in some circumstances. Up to 2.0 g/kg/day is beneficial to maximize muscle protein synthesis in resistance-training adults, with a maximum of 0.4 g/kg/meal (Egan, 2016). Furthermore it is a common misbelief that a high protein diet – alone – can impact bone health (Calvez et al., 2012).[4] 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 (Iglay et al., 2009; Campbell and Leidy, 2007).

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) (Kitada et al., 2019; Levine et al., 2014; Song et al., 2016; Ko et al., 2020). This is especially true for red meat (beef, pork, mutton and lamb) and even more so for processed meat (Kitada et al., 2019; Wolk, 2017).

Substitution of animal protein by plant protein is beneficial to reduce overall mortality (Song et al., 2016). 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 (Kitada et al., 2019). 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) (de l'Anses, 2016; Bohrer, 2017).[5]

To put these numbers in perspective with current diets, in the US, the average protein consumption is 1−1.5 g/kg/day (Fulgoni III, 2008).[6] Out of these, about 60% are meat and dairy sourced proteins (Pasiakos et al., 2015), 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.

1.3. Scope of this study: consumer-oriented review to guide low carbon footprint choices among meat and dairy proteins

For all these reasons, we investigate here the carbon footprint of meat and dairy proteins. Inspired by the works of Dyer et al. (2010), Vergé et al. (2013), Poore and Nemecek (2018), we aim for a measure of the carbon footprint per gram of protein for these different sources.

[1] Food loss at retail stores, in restaurants and household waste which have been estimated to be at least 30% in weight (Shepon et al., 2018).

[2] Starting from 115 g/day up to 340 g/day gives 230 – 680 kcal/day from meat; that is reduced by 30% to account for food loss and finally compared to the typical total intake 2000 kcal/day.

[3] This is established by several national health agencies. One review notes however that the lowest end of the acceptable macronutrient range (10% of total calories coming from proteins according to the dietary reference intakes (I. of Medicine, 2005)) is actually equivalent (Wolfe et al., 2017) to about 1.05 g/kg/day. This is quite larger than 0.8 g/kg/day.

[4] Yet a calcium deficient diet *can* impact bone health (Calvez et al., 2012).

[5] Other essential nutrients however cannot be found in plants, such as Vitamin B12, that is produced by bacteria (Bohrer, 2017)

[6] Similar numbers are found in Europe (Rousset et al., 2003).

We expose our methods in Section 2. This allows us to directly compare different sources of proteins (a variety of meats and dairy products) and determine which ones have the lowest carbon footprint (Section 3). This is especially relevant as it directly answers the consumer question of product selection for climate change mitigation, as far as proteins are concerned. Note that this is the first analysis that directly compares the carbon footprint of protein rich foods yet with very different protein contents (such as milk with 3, eggs with 10 and meat with 20 g protein/100 g edible food). We also investigate a very broad range of products, in particular through the comparison of milks from different ruminants (cows, goats, sheeps, and buffalo) and the variety of cheeses. This is in sharp contrast with former studies that are focused on meat (Dyer et al., 2010; Vergé et al., 2013; Poore and Nemecek, 2018).

We take our analysis closer to consumers by investigating specific dietary changes to reduce carbon footprint, taking into account regional discrepancies both in dietary patterns and in carbon footprints of products (Section 4). This allows us to find a "low CO_2" diet guide, that consists only of small animals (chicken, duck, rabbit), eggs and yogurts. This "low CO_2" diet, while providing the same total amount of proteins than reference diets, enables to reduce carbon footprints by 50%, reaching the IPCC 2030 target. Such a diet is a reliable guide notably across the world. Importantly, we have identified that vegetarian diets (with high amounts of dairy proteins) are not nearly as effective (only 20% reduction) as our "low CO_2" alternative. This highlights that as protein sources, dairy products in general do not have a low carbon footprint.

Finally, we discuss 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, nutritional questions and methodological questions (Section 5).

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 part of our diets with the largest carbon footprint, 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.

2. Methods

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) and the variability of dairy products (different cheeses and yogurts) are also compared.

2.1. World wide data

2.1.1. Protein content

Protein content ranges for the products investigated were taken from various national databases (Agency, 2002; F.C.F.F.V.C.D., 2019; S.R.L.R.V.C.A., 2019; Agence nationale de sécurité sanitaire de l'alimentation, 2020) – making sure that the methods for protein quantification in foods (Jones, 1941a) were consistent.

Protein content data has a lot of variability. For example, the breeding methods used change with time and affect the protein content (Agency, 2002). But also the breed itself and the sex of the animal (Kwasiborski et al., 2008). 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 (Agency, 2002; Kwasiborski et al., 2008). 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 that can be found in the meat and how they are ingested and used by our organism (Kwasiborski et al., 2008; Agence nationale de sécurité sanitaire de l'alimentation, 2020; Bohrer, 2017). To lessen such variability, here we discard processed foods such as patties, sausages, and other prepared meals.

This allows us to retain a range of protein content $P_{\min} - P_{\max}$ for each product. More information on the methods and the data retained in this study can be found in Appendix A.

2.1.2. Carbon footprint

Worldwide data on carbon footprint of the products investigated has been analyzed extensively in the past and meta-analyses are available (Clune et al., 2017; Poore and Nemecek, 2018). Therefore, we do not perform a worldwide meta-analysis here but rely on results of these previous works. More in detail, to assess the carbon footprint of meat and dairy products, we gather data from various sources (Clune et al., 2017; Poore and Nemecek, 2018; Colomb et al., 2015; Opio et al., 2013; Hamerschlag and Venkat, 2011; Williams et al., 2006; Beauchemin et al., 2010; Holland et al., 2014; Mogensen et al., 2015; Nguyen et al., 2010; Batalla et al., 2015; Pirlo et al., 2014; Robertson et al., 2015; Zucali et al., 2020; Gutiérrez-Peña et al., 2019). Our methodology for retaining data closely follows the protocol of Clune et al. (2017). Requirements to retain sources are that they are issued either through peer-reviewed meta-analysis data or data gathered by recognized national or international agencies. We require that any of 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 (1 kg of edible meat or dairy product, 1 kg of Fat and Protein Corrected Milk for milk). Where scarce data was available, *e.g.* for veal meat, among the few studies available, one study had a functional unit of 1 kg of carcass weight, and a $1 : 0.695$ conversion ratio to edible weight was used in line with Clune et al. (2017).

The boundaries of the LCAs retained for this study are from cradle to farm-gate (Colomb et al., 2015; Beauchemin et al., 2010; Nguyen et al., 2010; Mogensen et al., 2015; Batalla et al., 2015; Pirlo et al., 2014; Robertson et al., 2015; Zucali et al., 2020; Gutiérrez-Peña et al., 2019), or beyond. To be more specific they extend to Regional Distribution Centre (Clune et al., 2017), to retail (Poore and Nemecek, 2018; Opio et al., 2013) or to grave (Hamerschlag and Venkat, 2011). Transport and other life cycle stages beyond the farm-gate stage for the products considered here (meat and dairy) represent only a small fraction of GHG emissions contributing to the carbon footprint, compared to those emitted from cradle to farm-gate (Weber and Matthews, 2008) (in median only 77 $g_{CO_2}eq./100g$ edible (Clune et al., 2017)). These life cycle stages are therefore not relevant for meat and dairy, but would be for other products such as fresh vegetables (Weber and Matthews, 2008). In fact, such differences lie within the uncertainty range of the data. For example, median calculations from cradle to farm-gate (Colomb et al., 2015) show for a few products slightly *higher* climate change impacts than more complete assessments from *e.g.* cradle to Regional Distribution Centre (Clune et al., 2017) — potentially due to particular methodological differences in LCA assessment, that are beyond the scope of our work. In an effort to assess the carbon footprint of the most possible products, we conserve all data with boundaries at least from cradle to farm-gate. Furthermore, data variability will be assessed through statistical tests (see details in following paragraphs).

Minimum $C_{\mathrm{m,min}}$ and maximum $C_{\mathrm{m,max}}$ median values are taken from world averaged, meta-analysis (Clune et al., 2017; Poore and Nemecek, 2018) or national or international agencies (Colomb et al., 2015; Opio et al., 2013). Extreme ($C_{\min}$ and $C_{\max}$) values are taken from the reported extreme values of aforementioned references or from other national studies (Hamerschlag and Venkat, 2011; Williams et al., 2006; Beauchemin et al., 2010; Holland et al., 2014; Mogensen et al., 2015; Nguyen et al., 2010). For the different milk origins (goat, sheep, buffalo) where data is scarce, extreme values may be taken from LCAs of several farms (Batalla et al., 2015; Pirlo et al., 2014; Robertson et al., 2015; Zucali et al., 2020; Gutiérrez-Peña et al., 2019) (if they exceed other extreme values).

To assess that data was sufficient to investigate differences between products, we used a one way ANOVA test and found a p-value smaller than 0.04 ($<10^{-3}$ comparing the 12 main products investigated, 0.035 comparing the 4 milk origins), guaranteeing the validity of the data.

More information on the methods and the data retained in this study can be found in Appendix B.

2.1.3. 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 ($C_{\min} - C_{m,\min} - C_{m,\max} - C_{\max}$) and protein content ($P_{\min} - P_{\max}$) are quantified through ranges of values, we can obtain up to 8 ratios.

We present the data with center values as geometric averages based on the carbon footprint medians

$$\bar{C} = \left(\frac{C_{m,\min}}{P_{\min}} \frac{C_{m,\min}}{P_{\max}} \frac{C_{m,\max}}{P_{\min}} \frac{C_{m,\max}}{P_{\max}} \right)^{1/4}. \quad (1)$$

Additionally we report uncertainty ranges as $\left(\sqrt{\frac{C_{m,\min}}{P_{\min}} \frac{C_{m,\min}}{P_{\max}}} - \sqrt{\frac{C_{m,\max}}{P_{\min}} \frac{C_{m,\max}}{P_{\max}}} \right)$. Finally we use extreme values for error bars on plotted displays $\left(\frac{C_{\min}}{P_{\max}} - \frac{C_{\max}}{P_{\min}} \right)$. The use of geometric averages is favored over arithmetic averages for better data acknowledgment and to avoid data distortion by extreme values (McAlister, 1879; Fleming and Wallace, 1986). This is consistent with the idea of retaining median values for carbon footprints versus averages. Indeed they give a better representation of the *typical* emissions related to the consumption of a particular food. Specifically, (*i*) we are averaging ratios and the geometric mean treats the numerator and denominator equally. (*ii*) 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.

More information on the methods and the data retained in this study can be found in Appendix C.

2.2. Special products

We also investigate on a case by case basis the carbon footprint per g of protein of different dairy products. For this detailed investigation, we perform our own meta-analysis. Our analysis protocol follows closely that of Clune et al. (2017). The sources requirements are similar to those discussed above: in brief, data sources are issued from LCAs disclosed in peer-reviewed journals with sufficient information on the methods; the LCAs retained share the same functional units. The boundaries of the LCAs are at least from cradle to farm-gate. Most importantly, as this is a close-up investigation, the reference reporting on the carbon footprint should contain the protein content of the cheese or dairy product (whey powder, yogurt) investigated. Exceptions are made for specific cheeses, where the protein content of the product is not directly found in the reference reporting its carbon footprint, but as the cheese is branded or very well identified, its protein content is constant across the market and may be found on sellers databases.

More information on the methods and the data retained in this study can be found in Appendix D.

2.3. Regional averages

We also perform analyses of carbon footprint per g of protein on a regional scale. The regions retained for this study are regions where data was most accessible: Asia (South and East Asia), Europe, North America, South America and Oceania. A subset of 8 products is studied corresponding to the most consumed products (pork, chicken, beef, lamb, milk, cheese, yogurt and eggs).

2.3.1. Carbon footprint

For this investigation, we perform our own meta-analysis. Our analysis relies for the most part on the database accessible from Clune et al. (2017). Additional (recent, year > 2016) data sources are added to the database in a protocol following closely that of Clune et al. (2017). Additional data sources are issued from LCAs disclosed in peer-reviewed journals with sufficient information on the methods. The LCAs retained share the same functional units. The boundaries of the LCAs are at least from cradle to farm-gate. The full list of data sources is accessible as a Supplementary file.

For each region and each product, median values of carbon footprint ($C^{\text{region}}_{\text{m,product}}$) are calculated. One way ANOVA tests were performed for the different products in each region and found a p-value smaller than 0.04 (and even $< 10^{-3}$ for all regions except for Asia), validating the statistical significance of comparing the different products. For a few region-product pairs (Yogurt for Asia, Oceania and South America; Cheese for Asia), no data was found. This is correlated with low local consumption of the products. As a consequence the exact value of $C^{\text{region}}_{\text{m,product}}$ for dietary studies will not affect the results much. For these pairs, we evaluate the median carbon footprint of yogurt and cheese based on the carbon footprint for milk in that region, as milk production is the dominant contribution to dairy products carbon footprints (Finnegan et al., 2018; Mancini et al., 2019). In detail, for a specific region r we take $C^r_{\text{m,dairyproduct}} = C^r_{\text{m,milk}} \frac{C^{\text{world}}_{\text{m,dairyproduct}}}{C^{\text{world}}_{\text{m,milk}}}$ where $C^{\text{world}}_{\text{m,product}} = (C^{\text{product}}_{\text{m,min}} C^{\text{product}}_{\text{m,max}})^{1/2}$, where $C^{\text{product}}_{\text{m,min/max}}$ are the min, max median carbon footprints of a specific product based on world data, as discussed above.

2.3.2. Reference diets

We start from reference diets of countries present in the regions investigated. We retain the biggest countries in the regions of interest, namely: China and India (in Asia), the E.U. (in Europe), the United States of America (U.S.A. in North America), Brazil (in South America) and Australia (in Oceania). Average product consumption in each country (or group of countries) is obtained through national or international databases and reports (O. for Economic Co-operation and D. (OECD), 2020; Anon, 2020a; IDF, 2013; Anon, 2020b,c,d,e,f,g, 2021, 2020h). Note that product consumption does not correspond to products *actually* ingested by consumers but are *overestimated*. These numbers do not include food losses at the final stages of the food chain (Shepon et al., 2018). However, they do correspond to the food that was actually needed for consumption and therefore are the correct amounts to calculate carbon footprint on.

From the reference diets we calculate the total amount of meat and dairy protein intake in a region r as

$$P^r_{\text{tot}} = \sum_{\text{product}} \sqrt{P^{\text{product}}_{\min} P^{\text{product}}_{\max}} \times \text{product intake (g)}. \quad (2)$$

2.3.3. Alternative diets exploration

We also explore alternative diets. Our rule of work is to keep the total intake of animal protein P^r_{tot} 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

Table 1
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. As detailed in methods, the average carbon intensity $\bar{C}$ 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 $\bar{C}$
Beef	107	156	272	396	206 (129–329)
Lamb	118	147	200	249	172 (132–223)
Veal	72	98	NA	NA	84 (72–98)
Milk	32	39	74	90	54 (36–82)
Cheese	24	51	51	110	51 (35–75)
Pork	25	36	47	67	41 (30–56)
Turkey	28	32	32	36	32 (30–34)
Yogurt	11	32	24	70	27 (19–41)
Eggs	19	20	33	36	26 (20–34)
Chicken	15	20	31	41	25 (17–36)
Rabbit	21	23	22	24	23 (22–24)
Duck	16	18	29	34	23 (17–31)

and eggs only (ovo-lacto-vegetarian, abbreviated thereafter "Vegetarian"), (2) a low carbon footprint diet containing products that have a low carbon footprint with respect to protein intake, (this choice of products will appear natural after results exploration) namely chicken, yogurt and eggs, termed "Low CO_2" henceforth, (3) and finally the diet with potentially the lowest possible carbon footprint, containing only chicken (which we will show is the product with the lowest carbon footprint per g of protein), termed "Chicken".

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, for E.U. 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 to keep the total amount of protein constant. The relative amount of milk, cheese, yogurt and eggs is conserved.

2.3.4. Carbon footprint per diet

We calculate the carbon footprint per diet using either regional data ($C^r_{\text{m,product}}$) or world data ($C^{\text{world}}_{\text{m,product}} = (C^{\text{product}}_{\text{m,min}} C^{\text{product}}_{\text{m,max}})^{1/2}$) . The total carbon footprint is simply

$$C^{\text{world}/r}_{\text{diet}} = \sum_{\text{product}} C^{\text{world}/r}_{\text{m,product}} \times \text{diet product intake (100g)}. \tag{3}$$

More details on consumption and carbon footprint calculation for each countries (or group of countries) is reported in Appendix F.

3. Main results: the carbon footprint per g of meat and dairy proteins

Fig. 3c and Table 1 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. Dyer et al. (2010), Vergé et al. (2013), Poore and Nemecek (2018) for the few categories investigated in these studies.

3.1. Insight from carbon footprint per gram of (meat or dairy) protein

3.1.1. Protein content range and necessity for a carbon footprint per g of protein

The protein content of the different products is presented in Fig. 3a. While for most (unprocessed) meats (in red) the protein content range is roughly similar, around 20 g/100 g edible, the protein content of dairy products (in blue) is very broad, ranging from 3 g/100 g edible for milk to 36 g/100 g edible for some hard cooked cheeses. Within a single food category, the range itself can be very broad (from 17 – 36 g/100 g edible for cheese products — excluding for now cream cheese or cottage cheese that go as low as 8 g/100 g edible). This highlights the importance of a quantification of carbon footprint per g of protein.

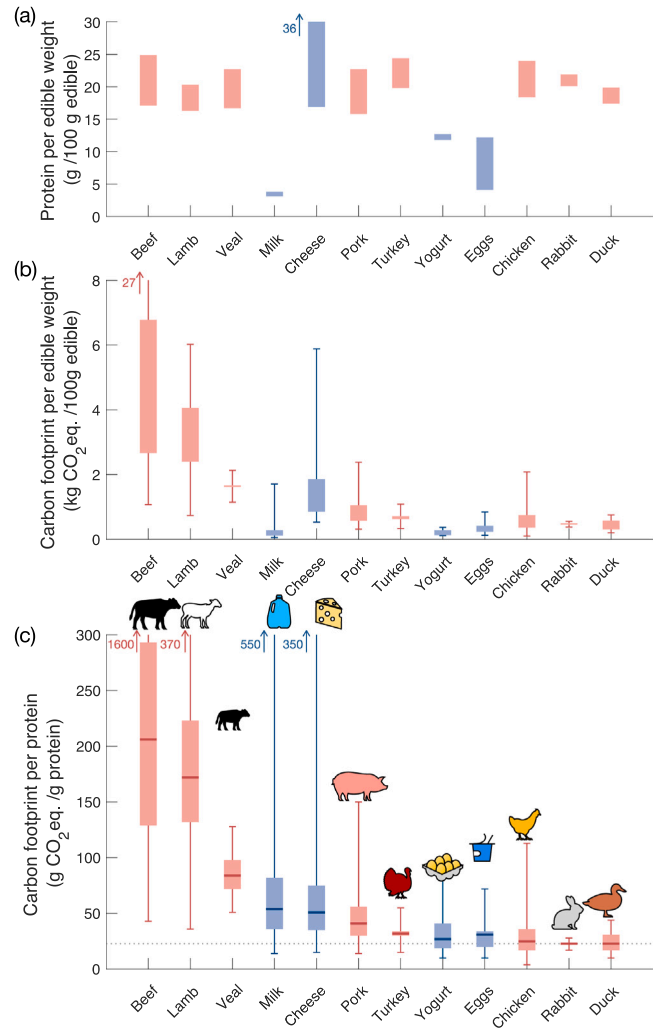

Fig. 3. Carbon footprint of animal proteins. Red colors refer to meat and blue colors to eggs and dairy. (a) Protein content range, (b) carbon footprint range and errorbars and (c) carbon footprint per g of protein retained and calculated in this study for different meat and dairy products. The dashed gray line in (c) is an indicator line corresponding to the lowest value of carbon footprint per g of protein found in this study.

3.1.2. Carbon footprint per g of edible food also spans a large range

The carbon footprint per edible weight of the different products is presented in Fig. 3b. Some food categories have exceptionally large carbon footprints, such as meat from beef, lamb and veal, ranging in average from 2 – 6 kg 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 – 300 g 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 investigated the carbon footprint per g of protein.

3.1.3. Carbon footprint per g of protein enables efficient comparison of protein rich foods

In Fig. 3c we present the carbon footprint of meat and dairy per g of protein.

We observe that some foods that have comparable protein content (such as meats) have very different carbon footprints per g of protein, spanning 2 orders of magnitude from about 20 g CO_2 eq./g protein for chicken, duck and rabbit to 200 g CO_2 eq./g protein for beef. This is mostly due to the very different carbon footprints per g of edible food of these meats. In fact 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. This is also in line with studies demonstrating that the carbon footprint of meat from beef calves consistently increases with slaughter age (Nguyen et al., 2010; Mogensen et al., 2015), due to proportionally higher feed intake required at later stages of the animals life.

Fig. 3c 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. Fig. 3c clearly shows that milk has a relatively high footprint of 54 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, such a methodology is extremely useful. 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, exclude carbon intensive meats such as beef and reduce dairy products such as milk.

Beyond the products investigated here, 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 (Williams et al., 2006; Röös et al., 2014). 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 (IPCC, 2006).[7] The variety of dairy products on the market is also quite large and we turn to investigate these in details in the following section.

3.2. 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 change impact. This is what we address in the following paragraphs.

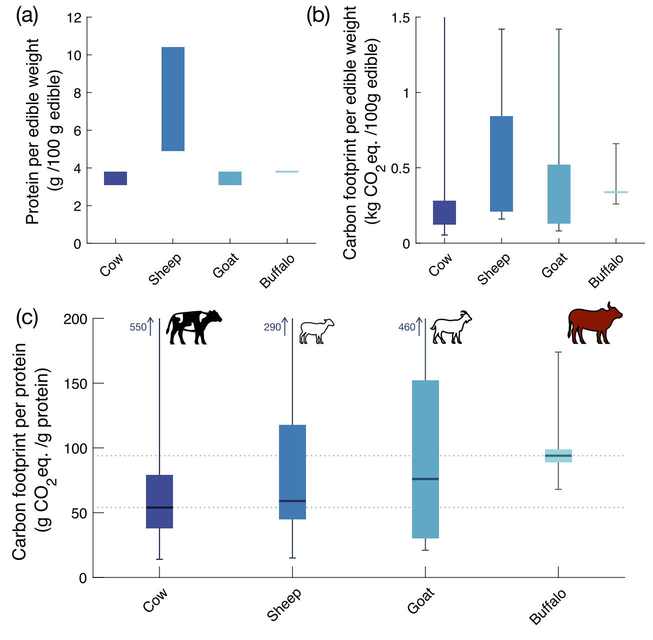

Fig. 4. Carbon footprint of various milks. Each shade of blue corresponds to an animal source. (a) Protein content range, (b) carbon footprint range and errorbars and (c) carbon footprint per g of protein retained and calculated in this study for different milks. The dotted lines in (c) are guides for the eye at the average cow and buffalo carbon footprints.

Table 2
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 $\bar{C}$
Cow's	32	39	74	90	54 (36–82)
Sheep's	20	43	81	171	59 (29–118)
Goat's	34	42	137	168	76 (36–152)
Buffalo's	89	NA	NA	NA	89 (NA)

3.2.1. 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%) (stats, 2020b). Therefore, one may wonder which source of milk is less carbon intensive among these different animals. Here we review the carbon footprint per gram of protein of these different milks.

Comparing different milk sources is especially interesting since the protein content of milk varies among species — see Fig. 4a. In particular, sheep milk has a protein content about twice 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. 4b. Overall this results in only slight differences between species when comparing the carbon footprint per g of protein — see Fig. 4c and Table 2. 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 sheep and goat milk. Finally buffalo milk appears 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.

In summary, milks from different species have a comparable carbon footprint per g of protein, with cow's milk being a little less intensive.

[7] Keeping for the assessment only manure emissions into consideration: Cattle emit 0.1 kg CH_4/kg live weight/ year (taking 53 kg CH_4 emitted per head per year per cattle, with an average live weight of 550 kg (Holland et al., 2014)). Deer emit a comparable 0.17 kg CH_4/kg live weight/year (with 20 kg CH_4 per head per year per deer, with an average live weight of 120 kg).

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, referred to as the FPCM factor (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 (Gutiérrez-Peña et al., 2019). Farm by farm analysis giving directly the carbon footprint per g of protein of the milk produced could be done to mitigate this issue, but the protein content of the produced milk is generally not reported.

3.2.2. Different cheeses do not just taste different

Milk is the main primary component of dairy products, and dairy products are extremely varied, especially for cheeses. 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 $3-5$ g protein/100 g for fresh yogurt, about 10 g protein/100 g for cream cheeses, common cheeses such as cheddar or mozzarella range between $15-25$ g protein/100 g and finally aged, very hard cheeses, such as parmesan, hit up to 36 g protein/100 g – see Fig. 5 and Table 11. However, cheeses with a higher protein content generally require more aging and thus have a larger carbon footprint (Kim et al., 2013). 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 footprint per g of protein for cheese.

Raw milk production is the main component of a cheese's carbon footprint thus most carbon quantification efforts for cheese are focused on milk produced for dairy plants (Finnegan et al., 2018; Mancini et al., 2019). 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 (Finnegan et al., 2018). The second most significant contributor to the carbon footprint of cheese is processing (Kim et al., 2013). Interestingly, industrial versus traditional techniques seem to perform quite as well carbon wise (Vagnoni et al., 2017). The aging part of processing is the most relevant part (Finnegan et al., 2018). For example, Dalla et al. Dall. Riva et al. (2018) compare the carbon footprint of aging for two cheeses, conducting a life cycle analysis restricted to the aging process. They find that through aging protein content increases from 24 to 28 g protein/100 g edible and carbon footprints rise from 1.32 to 1.61 kg CO_2 eq./kg edible (giving 5.5 to 5.7 g CO_2 eq./g protein). This hints to the fact that additional carbon footprints may well be compensated by higher protein content.

This compensation effect is far from trivial. In fact, one could expect the carbon footprint of proteins from cheese to simply increase concurrently with cheese aging. Yet cheese aging generates a number of co-products (whey, cream, butter, buttermilk *etc.*) to which part of the GHG emissions are also allocated (Kim et al., 2013; Famiglietti et al., 2019). The carbon content of cheese (specifically aged cheese) is significantly dependent on what carbon weight is attributed to those co-products (Santos et al., 2017; Famiglietti et al., 2019). Even in the same plant, differentiating the carbon footprint of two cheeses is quite subtle (Kim et al., 2013).

To investigate statistically whether higher protein content compensates for the GHG emissions related to aging, we present data from a number of LCA — see Table 11. We cover a wide range of cheeses, with a wide range of protein contents, and compare their carbon footprint per g of protein in Fig. 5. The correlation coefficient of the data is 0.68 and a least squares linear regression yields a regression coefficient $r^2 = 0.47$. This confirms that the carbon footprint 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 (as a protein source) is not relevant.

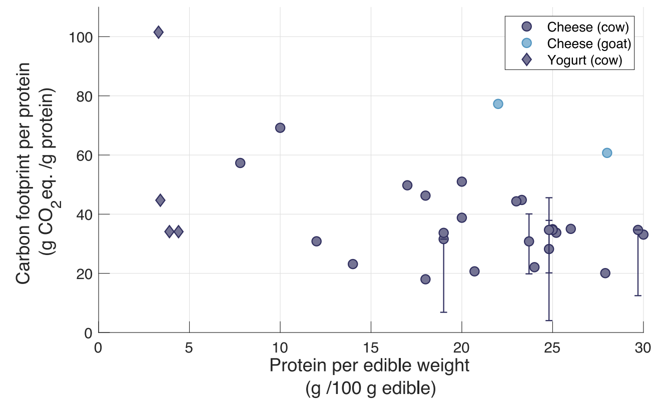

Fig. 5. Carbon footprint per g of protein of various dairy products, with a focus on cheese. The data is presented with respect to the protein content of the different dairy products. When confidence intervals were provided by the references investigated, they are reported on the graph.

3.2.3. Whey powders for protein supplements

The dairy product with the largest protein content is whey protein concentrate, with 80–90 g protein/100 g (Flysjö, 2012). For these products, data availability is extremely limited. Nonetheless, an extensive study allows to establish that whey concentrates emit about 20 g CO_2 eq./g protein (Flysjö, 2012) (with LCA boundaries from cradle to farm-gate), see Table 12. Concentrated whey is therefore one of the animal proteins with the lowest carbon footprint. This is consistent with another study that shows that whey, per protein serving, has one of the smallest carbon footprints among different high protein options (Berardy et al., 2019) (with similar LCA boundaries).

In contrast, standard whey products (not concentrated) have similar carbon footprint per g of protein as cheeses (Aguirre-Villegas et al., 2012; Kim et al., 2013; Flysjö et al., 2014) (similarly, with LCA boundaries from cradle to farm-gate), see Table 12.

3.2.4. The carbon footprint of butter

Analyzing the variety of cheeses highlights the critical role of co-products of the dairy industry in carbon footprint 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 cannot be disregarded. For example, in 2014, the worldwide average butter consumption was 700 g/capita/year (stats, 2020b) (reaching much higher and much lower values in specific countries). With a carbon footprint of 11.52 kg CO_2 eq./kg in average (Clune et al., 2017), 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 (100 g steaks, see Table 7).

Interestingly, butter is one of the most carbon intensive sources of fat per kg (Clune et al., 2017; Poore and Nemecek, 2018). 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.

4. Case study: carbon footprint 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

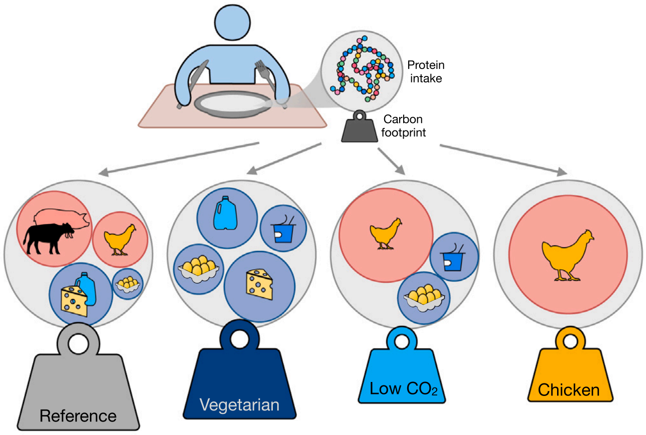

Fig. 6. Carbon footprint of different dietary choices starting from a reference E.U. diet. The plates show 4 different diets (reference, vegetarian (with eggs and dairy only), low CO_2 (with chicken, eggs and yogurt) and chicken). The disks in the plates represent proportional contributions of the various animal proteins to the diets. The carbon weights attached to each plate also have areas proportional to the relative carbon footprints.

techniques can have notable impact on the carbon footprint but seem to be insufficient to achieve IPCC targets (Garnett, 2011; Springmann et al., 2018; Willett et al., 2019). 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 (C. 4, 2020; Blonk et al., 2008; Friel et al., 2009; Werner et al., 2014; Hallström et al., 2015; Tyszler et al., 2016; Aleksandrowicz et al., 2016; Perignon et al., 2016; Vázquez-Rowe et al., 2017; Poore and Nemecek, 2018; González-García et al., 2018; Springmann et al., 2018; Willett et al., 2019; Chai et al., 2019). 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 Section 4.1. 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 Section 4.2.

4.1. Example of dietary changes based on the european average diet

We start by investigating in detail the carbon footprint of specific dietary choices on a representative diet, the average European Union (E.U.) diet. The carbon footprint per g of edible product in Europe is reported in Table 4. Table 3 recapitulates meat and dairy consumption in average in Europe and the content and carbon footprint of different alternative diets. We base our calculations on the data and methodology presented in the Methods Section 2.3.

The total protein intake coming from meat and dairy in the E.U. is 62.8 g/person/day. The carbon footprint of the diet based on carbon footprints calculated with world averages is 1331 kg CO_2 eq./year, while it is lower with regional averages, 908 kg CO_2 eq./year. This corresponds to overall efficient agricultural techniques in Europe.

The intake of the various food items in the different diets (vegetarian, low CO_2 and chicken) and the corresponding carbon footprints are reported in Table 3. Comparative carbon footprints and diet distribution among products is represented in Fig. 6. Comparing diets based on world averaged carbon footprints or on regional data yields very consistent results. We observe that the carbon footprint of the vegetarian diet is only 20% lower than that of 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 as far as carbon footprint is concerned. 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 other kinds of meat originating from small animals (duck, rabbit) would work. 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 footprint of diets when shifting from meat and dairy products to poultry was also noted by other works investigating complete or partial diet alternatives (González-García et al., 2018; Garnett, 2011; Hallström et al., 2015; Farchi et al., 2017; Aleksandrowicz et al., 2016; Blonk et al., 2008). Dairy rich diets, or diets replacing meat by dairy products are in general not found to yield significant improvement of the carbon footprint of the diet (Blonk et al., 2008; Hallström et al., 2015). 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 (Werner et al., 2014). This could slightly shift the balance, and we discuss these facts in more detail in Section 5.2.

4.2. Impact of specific dietary changes across the world

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 (Garnett, 2011). Here, we investigate dietary changes for populations in Brazil, in the U.S.A., in Australia, in China and in India. The exact same methodology as for the European diet was applied for these different countries, using both world averaged and regional carbon footprints — see Table 4. The results of carbon footprints across diets and countries are reported in detail in Appendix E and synthetically presented in Fig. 7.

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 disparate (see Fig. 7a), ranging from 80 g/day/capita in the U.S.A. to barely 10 g/day/capita in India. Even including 30% typical losses at the consumer level, this amounts to 56 g/day/capita of animal protein ingested in the U.S.A. which is quite significant compared to dietary recommendations for the total amount of proteins (48 – 64 g/day recommended for a 60 – 80 kg individual — see Section 1.2.). For India, in fact this represents only a small fraction of dietary recommendations.

The average carbon footprint per g of protein for these different countries is also quite different, see Fig. 7b. The world averaged data (open boxes in Fig. 7b) measures how diet composition influences the carbon footprint per g of protein. We find that diets that are rich in meat and especially in beef (such as the Brazilian, the American and the Australian diets) achieve the highest carbon footprint per g of protein. In comparison, diets with quite high amounts of chicken or vegetarian diets (such as Chinese and Indian diets) achieve slightly lower carbon footprints per g of protein (about 30% lower). Investigating the regional carbon footprint per g of protein of the diet (full boxes in Fig. 7b) shows that more economically developed countries typically achieve better footprints than their world counterparts, mostly due to improved agricultural methods and yields (Jianyi et al., 2015). Eventually the carbon footprint per g of protein of the American and Australian diets (high in beef, but with high yields) slightly outperforms the Chinese, Indian and Brazilian ones (10 – 30%).

Yet to compare diets for climate change mitigation, it is relevant to investigate the overall carbon footprint of the diet and not just the carbon footprint per g of protein. Economically highly developed countries are also those consuming the most meat and dairy, and therefore those that achieve the highest carbon footprint per year per

Table 3
Carbon footprint and protein intake from meat and dairy consumption for a reference European diet, and resulting carbon footprint 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. The low CO_2 diet contains chicken, eggs and yogurt.

Product	Reference	Vegetarian	Low CO_2	Chicken
Pork	97.3 (O. for Economic Co-operation and D. (OECD), 2020)	0	0	0
Chicken	64.7 (O. for Economic Co-operation and D. (OECD), 2020)	0	196.5	313.2
Beef	29.6 (O. for Economic Co-operation and D. (OECD), 2020)	0	0	0
Lamb	3.8 (O. for Economic Co-operation and D. (OECD), 2020)	0	0	0
Milk	178.1 (Anon, 2020a)	437.8	0	0
Cheese	50.4 (Anon, 2020a)	123.9	0	0
Yogurt	50.7 (IDF, 2013)[a]	124.7	154.2	0
Eggs	34.2 (Anon, 2020b)	84.1	103.9	0
Diet factor	1	2.5	3.0	4.8
Proteins (g/day)	65.8	65.8	65.8	65.8
Carbon footprint[b]	**1331**	**1052**	**605**	**598**
relative decrease	100%	79%	45%	45%
Carbon footprint[c]	**908**	**763**	**460**	**423**
relative decrease	100%	84%	51%	47%

[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 (Vatanparast et al., 2019; Anon, 2020h,c); dairy consumption evolution is smooth with time in Europe (Anon, 2020i).
[b]Calculated with world average, kg CO_2 eq./year.
[c]Calculated with Europe data, kg CO_2 eq./year.

Table 4
Regional carbon footprint data for products retained in this study.

Regional carbon intensity for meat and dairy products (C_m ($C_{min} - C_{max}$), g_{CO_2} eq./100g edible)					
Meat or dairy Product	Asia (AS)	Europe (E.U.)	North America (NA)	South America (SA)	Oceania (OC)
Pork	720	545	610	120	765
Chicken	740	360	307	373	385
Beef	3526	2576	2682	3392	2267
Lamb	3939	2856	3268	3788	1759
Milk	200	127	116	149	114
Cheese	1351[a]	880	872	1445	910
Yogurt	208[a]	135	154	155[a]	119[a]
Eggs	339	319	446	380	145

[a]Computed from world average figures ($\mu_{world} \cdot \frac{\mu^{milk}_{region}}{\mu^{milk}_{world}}$).

capita, even taking into account regional agricultural efficiency (see Fig. 7c, reference diet). We will now explore the results of potential dietary changes, keeping as a rule regional data for carbon footprints.

Interestingly, the switch to a vegetarian diet (including dairy and eggs) results in a small carbon footprint reduction (15%–30% reduction) and is insufficient in all countries to reach the IPCC 2030 target (of −45%). It is the most effective (achieving about 30% carbon footprint reduction) starting from the Brazilian and Chinese reference diets — see Fig. 7c and d, dark blue. 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, because dairy is not a major part of the reference diet. Eggs are quite low in carbon footprint 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.

Therefore, it is only natural to seek an alternative diet to the vegetarian diet to see if it is possible to achieve better carbon footprint reductions with alternative choices. We propose a “low CO_2” diet, that takes into account the results of carbon footprint per g of protein. Worldwide data (Table 1 and Fig. 3) suggests the following interesting products for carbon footprint reduction: meat from small animals (poultry, rabbit), eggs and yogurt. We therefore propose a “low CO_2” diet with eggs, chicken and yogurt only. We find that such dietary change is quite effective for all countries – see Fig. 7d, light blue – allowing carbon footprint reductions from 40 up to 70%. These reductions meet the requirements of the IPCC 2030 target. Low CO_2 dietary changes are especially effective for Brazil, America and Australia as the initial consumption of beef in these countries is relatively high compared to other countries (so the potential reduction is higher).

Finally we explore how the switch to a chicken only diet performs. Chicken is, regarding worldwide averages, the product with the lowest carbon footprint per g of protein, and therefore a natural choice. We find that such a restriction does not improve carbon footprint reduction for all countries — see Fig. 7d, yellow. For some countries a marginal reduction as compared to the low CO_2 is achieved, while for others a higher carbon footprint than the "low CO2" diet, or even the vegetarian diet, is reached. In fact, although chicken is, regarding worldwide averages, the product with the lowest carbon footprint per g of protein, it is not necessarily the case in all countries. For example, in China, eggs perform much better than chicken, potentially due to different agricultural management techniques compared to other countries (Luo et al., 2015; Jianyi et al., 2015). The mix of products in the low CO_2 diet thus avoids small regional disparities.

Overall this demonstrates that a shift to the low CO_2 diet (*i*) has a drastic impact over the carbon footprint of an individual from meat and dairy proteins and (*ii*) is a consistently good alternative diet throughout large regions of the world.

5. Discussion: a low carbon footprint consumer guide

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

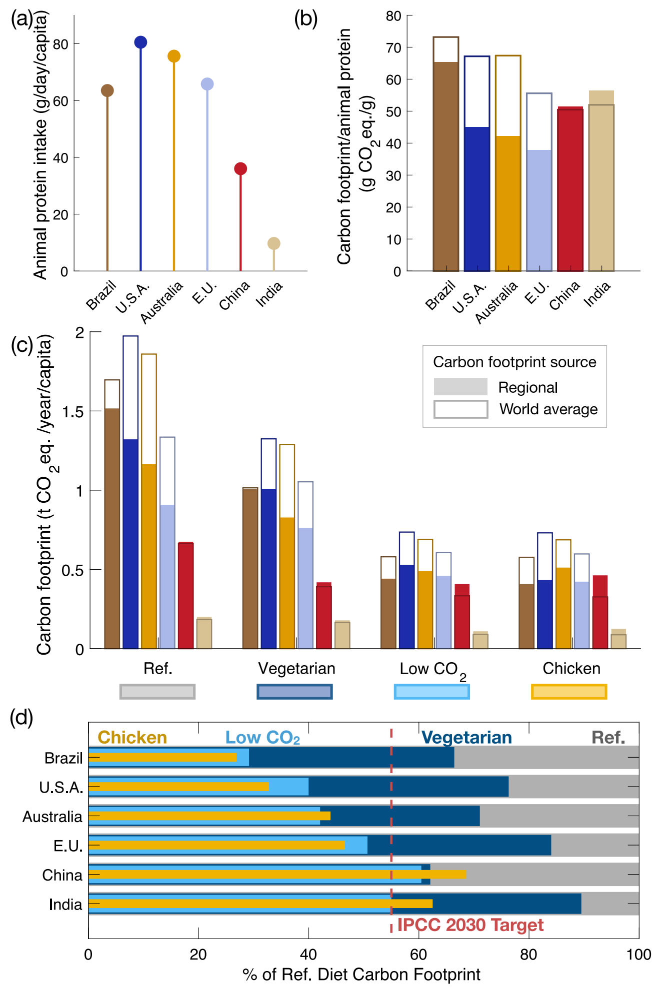

Fig. 7. Carbon footprint reduction for different dietary choices in different countries. (a) Daily animal protein intake (from meat and dairy, excluding complementary protein intake in the form of *e.g.* protein powder) for 6 representative countries; (b) Average carbon footprint per animal protein; (c) Yearly carbon footprint of the 4 different diets investigated in Fig. 6 for the 6 countries; (d) Relative carbon footprint reduction for the different diets investigated for the 5 countries comparing data calculated with regional carbon footprints.

5.1. Low carbon footprint dietary guide

5.1.1. The general low co_2 diet: chicken, eggs, and yogurt

We have found that dietary choices within meat and dairy that achieve a low carbon footprint overall, reaching the IPCC 2030 Target, include meats from small animals (chicken, duck, rabbit), eggs, and dairy products with little preparation and high protein content (such as yogurts, but not milk). Such dietary choices allow for significant carbon footprint reduction in most regions of the world (the Americas, Europe, South and South East Asia, and Oceania). In other parts of the world similar conclusions may likely hold as well but data on carbon footprints of dairy products is insufficient to explore the question in depth.

Yet consumers may be faced with more detailed questions than just what type of meat and dairy to eat but also in *what* quantity. For example, the consumption of a 125 g steak of beef per year may not significantly change the overall carbon footprint of an individual's diet, but 125 g a week could. To facilitate science informed decisions, and as part of a dissemination effort, we provide a simple online tool – see Fig. 8 and Anon (0000) – allowing anyone to estimate their carbon

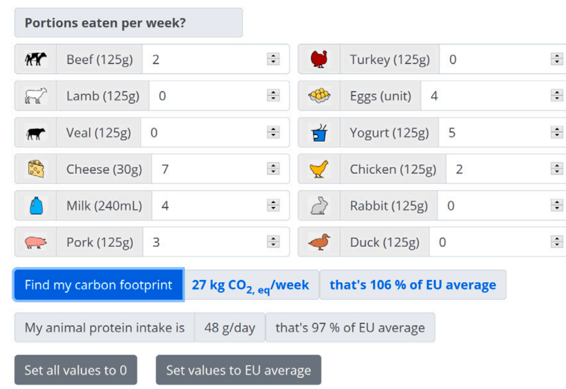

Fig. 8. Example use of our online tool (Anon, 0000) (accessible at http://www.sciriousgecko.com/ArticleMeat.html) for a quick assessment of the carbon footprint of meat and dairy proteins.

footprint from meat and dairy products. The tool allows the user to enter their weekly consumption of the most common meat and dairy products in a single online interface and returns the yearly carbon footprint and daily protein intake. Further details on the online tool implementation and source may be found in Appendix F.

Beyond the question of quantity, consumers may also want to choose the *origin* of meat and dairy products bought. These are questions we discuss below.

5.1.2. Local or imported meat?

Consumers are generally keen on buying and consuming "locally" produced foods (Murdoch et al., 2000; Low et al., 2015). Key driving factors include – but are not restricted to – associating health and quality with local products (Murdoch et al., 2000; Low et al., 2015), concerns of helping the local economy to thrive and engaging in sustainability (Low et al., 2015; Brunori et al., 2016). 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, compared to the life cycle stages from cradle to farm gate, transport typically represents an infinitesimal fraction of the carbon footprint (Williams et al., 2006; Poore and Nemecek, 2018; Saunders et al., 2008; Weber and Matthews, 2008; Williams et al., 2008). In fact breeding, crop growing for feeding and manure emissions at the farm represent significantly much more emissions (Williams et al., 2006, 2008; Poore and Nemecek, 2018). 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 (Saunders et al., 2008).[8] In this example, the system boundaries are from cradle to farm gate, but include transport from New Zealand to the UK for the New Zealand meat. 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 (Saunders et al., 2008; Weber and Matthews, 2008). As a rule of thumb, production methods are the main factor determining *ruminant* meat and dairy proteins' carbon footprint.

However, when specializing into sub-products of the dairy industry such as cheese, reducing the transport footprint may significantly

[8] Doing the simple ratio of their numbers $2849/688 \simeq 4.1$ of the respective carbon intensities for lamb; and $2921/1423 \simeq 2$ for milk solids.

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 Dall Riva et al. (2017) for the production of mozzarella in the Italian dairy sector for an LCA from cradle to grave).

While for ruminant meats and dairy, emissions linked to transport remains under 2% of the total, for poultry and pig meats they average at about 5% (Poore and Nemecek, 2018). Therefore, consuming locally sourced pork and poultry (or transported with low-carbon footprint means) may be consistent with a low-carbon intensity endeavor. However, the impact of transport is still quite marginal compared to world-wide differences in carbon footprints (see Table 4).

To put it in a nutshell, in general locally sourced meat and dairy are not a guarantee of lower carbon footprints. The question has to be sorted on a case by case basis (Williams et al., 2008; Garnett, 2011).

5.1.3. Organic or non-organic?

Consumers also show increased interest in buying organic food products, including for meat and dairy products (Santeramo et al., 2018; Dimitri and Oberholtzer, 2009; Grunert, 2006). Similarly, when trying to minimize carbon footprint, one may ask which agricultural method is the best (here we will focus on organic versus non-organic as this is the most common label seen by consumers). 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 studies directly comparing organic and non-organic systems with the same methods.

We first tackle the subject of ruminant meat and dairy. A study on farming in Japan found that the global warming potential of organic versus conventional systems for beef was similar (Tsutsumi et al., 2018) (for cradle to farm-gate boundaries). In the UK, organic beef and dairy emits about 15% more than conventional farming (Williams et al., 2006) (for cradle to farm-gate boundaries), while organic sheep farms emit 42% less CO_2 equivalent. In Italy, a case study found that organic beef emits even up to 30% more (Buratti et al., 2017) (for cradle to farm-gate boundaries). A meta-analysis conducted recently reveals that organic cow milk emits 10% less CO_2 equivalents than conventional (Lorenz et al., 2019) (for cradle to farm-gate boundaries). 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 (Flysjö et al., 2012). 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 (Niggli et al., 2009).

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) (Williams et al., 2006; Tsutsumi et al., 2018; Lorenz et al., 2019). 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 greenhouse gases (Williams et al., 2006) – although that depends on the specifics of manure management (Niggli et al., 2009). Other studies suggest that organic feed results in more enteric fermentation (Buratti et al., 2017). Noteworthy, optimization of production by larger farms does not seem to impact significantly the carbon footprint of dairy production (Nemecek et al., 2011) (for cradle to farm gate boundaries). 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 (Kool et al., 2009), while in the UK organic pork was found to emit 11% less (Williams et al., 2006) (both studies have boundaries from cradle to farm-gate). For poultry in the UK, organic farms emit 46% more CO_2 equivalents and free-range non organic (versus cage non organic) emit 20% more than conventional (Williams et al., 2006). Similarly for eggs in the UK, organic farms emit 27% more CO_2 equivalents and free-range non organic farms emit 12% more than conventional (Williams et al., 2006). In the UK, “optimized” breeding in conventional farms, relying on an efficient use of space, explain the relative better performance of conventional methods (Williams et al., 2006). Another important contributing factor is more important grazing in organic systems, that tends to increase emissions (Kool et al., 2009). Similarly as for ruminants, the variety of results for non-ruminant meats makes it difficult to conclude on a generic trend.

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 (Williams et al., 2006; Kool et al., 2009). However non-organic products require in particular more synthetic pesticides (Williams et al., 2006; Niggli et al., 2009), which have their own detrimental environmental impact (Tilman et al., 2001; Topping et al., 2020). Noteworthy, organic livestock breeding – and other “sustainable” breeding approaches – can be beneficial in many more ways (such as introducing nitrogen fixing plants to enhance soil quality), that are further detailed for example in Niggli et al. (2009).

The current data on organic versus non-organic production systems suggests that in general organic meat and dairy production leads to a slightly higher carbon footprint than non-organic, especially via land use change. Modern techniques can help mitigate this effect (Niggli et al., 2009). Importantly, 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 (Niggli et al., 2009). 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.

5.2. A nutrition-oriented note on dietary changes

Beyond protein intake, other nutritional aspects should be considered when considering alternative diets (Werner et al., 2014; Perignon et al., 2016; González-García et al., 2018). This is a difficult task, as dietary reference points, *i.e.* most current average diets, are not necessarily nutritionally complete (Tyszler et al., 2016). 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 (Anon, 2020j). Lack of iron is consistently seen in another study investigating micronutrients of a complete average diet (Tyszler et al., 2016). 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 (Werner et al., 2014). 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) (Perignon et al., 2016; Weaver and Plawecki, 1994) or fortified products (such

Table 5
Protein Content of common meat-based products. All of the data reported is given without bones (Agency, 2002), and for raw meat.

Meat-based product	Protein content range $P_{min} - P_{max}$ (g protein/100 g raw)	List of references used
Beef	17.1–24.9	*Trimmed parts* (lean) 22.5 (Agency, 2002), (fat) 18.9 (Agency, 2002) (minced) 19.7 (Agency, 2002), (rumsteack) 20.7 (Agency, 2002) (loin) 22.2–24.9 (F.C.F.F.V.C.D., 2019) (round) 23.4–23.7 (F.C.F.F.V.C.D., 2019), (all) 18.4–24.1 (Agence nationale de sécurité sanitaire de l'alimentation, 2020); *Ribs* 18.8 (Agency, 2002); *Stewing steak* 22.1 (Agency, 2002), 21.2–24 (Agence nationale de sécurité sanitaire de l'alimentation, 2020); *burgers* 17.1 (Agency, 2002), (lean and not) 17.3-21.9 (Agence nationale de sécurité sanitaire de l'alimentation, 2020)
Veal	16.7–22.7[a]	*Scallops* 20.7 (Agence nationale de sécurité sanitaire de l'alimentation, 2020), 22.7 (Agency, 2002); *burgers* 16.7–17.2 (Agence nationale de sécurité sanitaire de l'alimentation, 2020); *other* 18.3–27.3 (Agence nationale de sécurité sanitaire de l'alimentation, 2020), 16.95–20.92 (S.R.L.R.V.C.A., 2019)
Pork	15.8-22.7[b]	*Bacon* 16.5 (Agency, 2002), 15.8 (Agency, 2002), 17 (Agence nationale de sécurité sanitaire de l'alimentation, 2020); *ham* (salami) 18.4 (Agency, 2002), 17.4 (Agency, 2002) (ham, 4% fat) 20.9 (Agency, 2002) (cooked) 15.1–18.1 (F.C.F.F.V.C.D., 2019), 18–21.6 (Agence nationale de sécurité sanitaire de l'alimentation, 2020) (uncured) 24.2–30.4 (Agence nationale de sécurité sanitaire de l'alimentation, 2020); *trimmed* 18.6–21.8 (Agency, 2002) 15.9–22.7 (Agence nationale de sécurité sanitaire de l'alimentation, 2020); *sausages* 11.9–13.6 (Agency, 2002), 11.8–17.3 (Agence nationale de sécurité sanitaire de l'alimentation, 2020)
Chicken	18.4–24[c]	*Dark meat, such as thighs* 20.9–24.0 (Agency, 2002); *Dark and white* 18.4–23.5 (Agence nationale de sécurité sanitaire de l'alimentation, 2020);*roasting, meat only* 20.44 (S.R.L.R.V.C.A., 2019); *ground* 17.04–17.93 (S.R.L.R.V.C.A., 2019); *broilers or fryers, variable content of skin* 17.88– 22.2 (S.R.L.R.V.C.A., 2019)
Turkey	19.8–24.4[c]	*Dark meat, such as thighs* 24.4 (Agency, 2002), 20.6, 21.28 (S.R.L.R.V.C.A., 2019); *White meat, such as breasts and wings* 20.4 (Agency, 2002), 21.28 (S.R.L.R.V.C.A., 2019), 20.22 (S.R.L.R.V.C.A., 2019); *Dark and white* 19.8–23.4 (Agence nationale de sécurité sanitaire de l'alimentation, 2020); *Sausage* 18.79 (S.R.L.R.V.C.A., 2019); *Ground* 19.66 (S.R.L.R.V.C.A., 2019); *other* 15.6–19.7 (F.C.F.F.V.C.D., 2019), 18.79 (S.R.L.R.V.C.A., 2019)
Lamb	16.3–20.3	*Loin chops, cutlets* 16.3 (Agency, 2002), 17.6 (Agency, 2002); *trimmed, minced* 20.2 (Agency, 2002), 19.1 (Agency, 2002); *shoulder* 17.6 (Agency, 2002), 17.5–20 (Agence nationale de sécurité sanitaire de l'alimentation, 2020); *other* 20.3 (S.R.L.R.V.C.A., 2019)
Duck	17.4–19.9	19.7 (Agency, 2002), 17.4–19.4 (Agence nationale de sécurité sanitaire de l'alimentation, 2020), 18.28–19.85 (S.R.L.R.V.C.A., 2019)
Rabbit	20.1–21.9	21.9 (Agency, 2002), 20.4–21.8 (Agence nationale de sécurité sanitaire de l'alimentation, 2020), 20.05 (S.R.L.R.V.C.A., 2019)
Game meat[d]	*20.7–23.7*	*deer, roe, pheasant, boar, rabbit* 20.7–23.7 (Agence nationale de sécurité sanitaire de l'alimentation, 2020); *bison, deer, boar, rabbit* 21.51, 21.62, 21.79, 22.96 (S.R.L.R.V.C.A., 2019)
Ostrich[d]	*20.2–23.7*	20.2 (Agence nationale de sécurité sanitaire de l'alimentation, 2020) 20.22–23.69 (S.R.L.R.V.C.A., 2019)
Organ meats[d,e]	*7.1–21.8*	*Pork* 7.1 (Agency, 2002), 12.1 (Agence nationale de sécurité sanitaire de l'alimentation, 2020) *Beef* 10.3–21.8 (Agence nationale de sécurité sanitaire de l'alimentation, 2020)

[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.

as plant-based beverages). Larger dietary shifts require more careful nutritional adaptations (Perignon et al., 2016).

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 (Aleksandrowicz et al., 2016). For example, the reduction of livestock product consumption by 30% was projected to decrease the risk of ischaemic heart disease by 15% (Friel et al., 2009). This fact was corroborated by other studies (Farchi et al., 2017). Moreover, animal protein intake leads to higher blood serum levels of the hormone insulin-like growth factor 1 (IGF-1) (Allen et al., 2002). These higher levels are important risk factors in several types of cancer (Fürstenberger and Senn, 2002; Yang et al., 2011) (prostate (Rowlands et al., 2009; Harrison et al., 2017); colorectal (Farchi et al., 2017), and breast cancer (Hormones et al., 2010) for example). Furthermore, trading animal proteins for plant-based proteins in a diet comes with an even greater reduction in carbon footprint (Poore and Nemecek, 2018; Clune et al., 2017). 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 (Werner et al., 2014); similarly pork contains more micronutrients than chicken (Tyszler et al., 2016). 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 (Melina et al., 2016; Niggli et al., 2009) but some studies fail to compare diets where all micronutrient targets are reached (Werner et al., 2014)). 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 (Melina et al., 2016). For example, although dairy is potentially interesting for its high level in calcium, high dairy intake may be associated with higher risk of prostate cancer (Aune et al., 2015) via IGF-1 (Harrison et al., 2017). 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.

Table 6
Protein Content of common dairy products; As an indicative note, a typical egg weighs between 40 and 70 grams (Anon, 2020k), resulting in about 4–9 g of protein per egg.

Protein Content of common dairy products and eggs		
Dairy product	Protein content range $P_{min} - P_{max}$ (g protein/100 g raw)	List of references used
Milk (cow, skimmed to whole)	3.1–3.8	3.3–3.4 (*average, UHT or pasteurized*) (Agency, 2002), 3.24–3.8 (Agence nationale de sécurité sanitaire de l'alimentation, 2020), 3.06–4.02 (F.C.F.F.V.C.D., 2019)
Milk (goat)	3.1–3.8	3.22–3.77 (Agence nationale de sécurité sanitaire de l'alimentation, 2020) 3.1 (*average, UHT or pasteurized*) (Agency, 2002), 3.56 (S.R.L.R.V.C.A., 2019)
20.5–23.7 Milk (sheep)	4.9–10.4	4.85–10.4 (Pulina et al., 2005) 5.4 *(average, raw*) (Agency, 2002), 5.98 (S.R.L.R.V.C.A., 2019), 5.68 (Agence nationale de sécurité sanitaire de l'alimentation, 2020)
Milk (Buffalo)	3.8	3.75 (S.R.L.R.V.C.A., 2019)
Fresh cheese (cow)	7.7–13.3	12.6 (*cottage cheese*) (Agency, 2002), 7.65 (Agence nationale de sécurité sanitaire de l'alimentation, 2020), 8.55–13.3 (F.C.F.F.V.C.D., 2019)
Soft cheese (cow)	16.9–25.6	*Brie* 17.3–22 (Agence nationale de sécurité sanitaire de l'alimentation, 2020) 20.3 (Agency, 2002); *camembert* 21.5 (Agency, 2002), 21 (Agence nationale de sécurité sanitaire de l'alimentation, 2020); *blue cheeses* 20.5–23.7 (Agency, 2002) 19.6 (Agence nationale de sécurité sanitaire de l'alimentation, 2020); *mozzarella* 18.6 (Agency, 2002), 16.9 (Agence nationale de sécurité sanitaire de l'alimentation, 2020), 20.9–25.6 (F.C.F.F.V.C.D., 2019)
Soft hard cheese (cow)	20.4–24.6	*Reblochon* 20.4 (Agence nationale de sécurité sanitaire de l'alimentation, 2020); *saint-nectaire* 22.5 (Agence nationale de sécurité sanitaire de l'alimentation, 2020); *raclette* 24.6 (Agence nationale de sécurité sanitaire de l'alimentation, 2020)
Cooked cheese (cow)	21.5–36.2	*Cheddar* 24 (Agence nationale de sécurité sanitaire de l'alimentation, 2020), 25.4 (Agency, 2002), 21.5–25.6 (F.C.F.F.V.C.D., 2019); *parmesan* 34.1–34.5 (Agence nationale de sécurité sanitaire de l'alimentation, 2020), 36.2 (Agency, 2002), 34.1 (Agence nationale de sécurité sanitaire de l'alimentation, 2020); *comte and other related cooked cheeses* 27.1–28.4 (Agence nationale de sécurité sanitaire de l'alimentation, 2020); *swiss cheese* 25.7–28.3 (F.C.F.F.V.C.D., 2019)
Fresh cheese (goat, sheep)	14.8–20.7	*Feta* 14.8 (Agence nationale de sécurité sanitaire de l'alimentation, 2020) 15.6 (Agency, 2002); *other* 19.8–20.7 (Agence nationale de sécurité sanitaire de l'alimentation, 2020)
yogurt (plain to low fat, cow)	4.1–5.7	4.12–4.82 (Agence nationale de sécurité sanitaire de l'alimentation, 2020) 4.8–5.7 (Agency, 2002), 5.25 (S.R.L.R.V.C.A., 2019)
yogurt, greek style (low fat, cow)	6.9–12.2	7.95 (Agence nationale de sécurité sanitaire de l'alimentation, 2020)-9.89 (Agence nationale de sécurité sanitaire de l'alimentation, 2020) 6.89–12.2 (F.C.F.F.V.C.D., 2019)
Eggs (chicken)	11.8–12.7	12.5 (Agency, 2002), 11.8–12.7 (F.C.F.F.V.C.D., 2019), 12.7 (Agence nationale de sécurité sanitaire de l'alimentation, 2020)

5.3. A note on allocation: what about protein allocation?

When comparing the carbon footprint of different foods, we have noticed how crucial distribution of GHG emissions among sub-products may be (the canonical example of these being distribution between meat and milk in a dairy farm) (Poore and Nemecek, 2018). In general, when GHG emissions cannot be separated, allocation is performed on an economical basis – this is the case in all of the studies investigated and retained here for analysis. In a protein-focused perspective, one might expect that eventually milk and beef, two main products generated by cow breeding, should have the same carbon footprint per g of protein. It is therefore only natural to ask how a protein allocation may affect the results investigated here. Performing a complete LCA with protein allocation and comparison with other allocation methods is beyond the scope of this study. Instead, and in line with our pedagogical view, we explore the consequences on a concrete – admittedly very simplified – example of protein allocation.

Let us consider a dairy farm producing both milk and meat. We assume that 100 (arbitrary) carbon units are necessary for the production of 25 g of meat and 1 kg of milk (typical production ratio (Flysjö et al., 2011)). We now seek the carbon footprint per g of protein for milk and meat with two allocation scenarios for the carbon units: (1) protein allocation and (2) economic allocation. Taking data from Tables 5 and 6 ($\simeq$ 20 g protein/100 g of edible meat and 3.3 g protein/ 100 g of milk) we get 5 g of meat protein per 33 g of milk proteins; a total of 38 g proteins. The protein based allocation (1) gives $100/38 = 2.63$ carbon units/g of protein be it milk or beef. Taking a price of 0.9\$/kg of milk and 11\$/kg for meat (U.D. of Agriculture (USDA) economic research service, 2020) makes 0.9\$ of milk and 0.275 \$ of meat, a price ratio of 70%. Thus the economic allocation (2) attributes 70 carbon units to milk (respectively 30 to meat), making $70/33 = 2.1$ carbon units per kg of milk protein and $30/5 = 6$ carbon units for meat protein. Note that the coarse-grained numbers computed here give a good representation of more advanced analyses (with boundaries within the dairy system only (Flysjö et al., 2011) or beyond from cradle to retail (Poore and Nemecek, 2018)).

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 three times higher as for 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 footprint of meat (and only barely overestimates that of milk). As a result, protein allocation may improve the carbon footprint per g of protein of beef, but not of milk. Therefore, both milk and beef have very high carbon footprints per g of protein (compared to other products such as poultry) regardless of the allocation method.[9]

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

[9] Note that the numbers obtained here show that for economic allocation, beef proteins have a carbon footprint 3 times as high as milk proteins. Yet in Table 7 we find that beef proteins have a carbon footprint 4 times as high is milk proteins. This is due in particular to the fact that beef does not come solely from dairy farms (Beauchemin et al., 2010; Poore and Nemecek, 2018).

Table 7
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./100 g edible) [Min – Median$_{min}$-Median$_{max}$ – Max] $C_{min} - C_{m,min}$ - $C_{m,max} - C_{max}$	List of meta-analysis used, with carbon footprint data ($g\ CO_2$ eq./100 g edible) (**bold font** corresponds to retained data for carbon footprint range)
Beef	1074 – 2661-6780 – 26920	2700 (Hamerschlag and Venkat, 2011) (*single LCA, USA, average methods*); 3100 (Beauchemin et al., 2010; Holland et al., 2014) (*Average, Canada*) ; **2661** (**1074**-10950)[a] (Clune et al., 2017) (*meta-analysis*); 6040 (3760-**26920**)[b] (Poore and Nemecek, 2018) (*meta-analysis*); 2860 ± 30% (Colomb et al., 2015) (*Average, national agency, France*); **6780** (1100-11050)[c] (Opio et al., 2013) (*world average emissions, FAO*);
Veal	1148 – 1640-NA – 2132	**1280-1650** (Mogensen et al., 2015)(*different age of slaughter, typical Danish/Swedish farms*)[d]; ; 1600-1990 (Nguyen et al., 2010) (*different age of slaughter, typical E.U.farms*); **1640 ± 30%** (Colomb et al., 2015) (*Average, national agency, France*)
Pork	320 – 577-1060 – 2380	1210 (Hamerschlag and Venkat, 2011) (*single LCA, USA, average methods*); **577** (**320**-1186)[a] (Clune et al., 2017) (*meta-analysis*); **1060** (690-**2380**)[b] (Poore and Nemecek, 2018) (*meta-analysis*); 589 (Colomb et al., 2015) (*Average, national agency, France*)
Lamb	740 – 2400-4060 – 6020	3920 (Hamerschlag and Venkat, 2011) (*single LCA, USA, average methods*); 2558 (1005-5670)[a] (Clune et al., 2017) (*meta-analysis*); **4060** (2370-**6020**)[b] (Poore and Nemecek, 2018) (*meta-analysis, no distinction between Lamb and Mutton*); 3300 ± 30% (Colomb et al., 2015) (*Average, national agency, France*); **2400** (**740**-4970)[c] (Opio et al., 2013) (*world average emissions, FAO*)
Chicken	106 – 365-750 – 2080	690 (Hamerschlag and Venkat, 2011) (*single LCA, USA, average methods*); **365** (**106**-998)[a] (Clune et al., 2017) (*meta-analysis*); **750** (400-**2080**)[b] (Poore and Nemecek, 2018) (*meta-analysis*); 475 ± 30% (Colomb et al., 2015) (*Average, national agency, France*)
Turkey	334 – 628-717 – 1090	**1090**(Hamerschlag and Venkat, 2011) (*single LCA, USA, average methods*); **717** (**334**-849)[a] (Clune et al., 2017) (*meta-analysis*); **628**± 30% (Colomb et al., 2015) (*Average, national agency, France*)
Duck	207 – 309-583 – 758	**309** (**207**-410)[a] (Clune et al., 2017) (*meta-analysis*); **583 ± 30%** (Colomb et al., 2015) (*Average, national agency, France*)
Rabbit	382 – 470-486 – 558	**470** (**382**-558)[a] (Clune et al., 2017) (*meta-analysis*); **486 ± 30%** (Colomb et al., 2015) (*Average, national agency, France*)

[a]Numbers reported here correspond to: median (min–max) as given in Clune et al. (2017).
[b]Numbers reported here correspond to: median (5th percentile-95th percentile) as given in Poore and Nemecek (2018). Poore and Nemecek (2018) does not provide minimum or maximum values used and hence we choose to use (5th percentile-95th percentile) as good representatives of these values.
[c]Numbers reported here correspond to: average (min–max) where the average is the LCA for the total world production, and the variation of footprint corresponds to varying yields across the world. The LCA is from cradle to retail.
[d]Using carcass weight to edible weight values reported in Clune et al. (2017).

nearly carbon-free (IDF, 2010). 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 further comparison of allocation methods we refer the reader to Flysjö et al. (2011), IDF (2010), Dall Riva et al. (2017), Canellada et al. (2018), Poore and Nemecek (2018).

6. 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 proteins. 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, lightly processed, dairy (such as yogurt) have a much lower carbon footprint. This methodology and the data generated allows us to draw guidelines for low carbon footprint dietary choices within meat and dairy. Interestingly, a change to ovo-lacto-vegetarian diet results in a low improvement of the carbon footprint. A change to a low CO_2 diet, containing small poultry, yogurt, and eggs results in a drastic, 50 %, improvement, allowing to reach the IPCC 2030 target of 45% reduction (Hoegh-Guldberg et al., 2018). Such an alternative diet is easily achievable for a consumer wishing to maintain its total consumption of meat and dairy proteins, and allows significant improvement.

Furthermore, we have investigated several other 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 limited data availability, showing that some consumer-oriented questions are hard to answer at this stage. Nonetheless, among milk origins we find that cow's milk has the lowest carbon footprint compared to other ruminants. We also find that cheeses have comparable carbon footprints per g of protein regardless of aging time. Finally, we identified that locally sourced meats may not have a lower carbon footprint than imported ones. On the other hand, dairy processed directly on the farm may have a significantly reduced footprint.

To reach IPCC targets over total food-related emissions, the low carbon diet would not be sufficient since comparable improvements cannot necessarily be obtained over all food sources (Clune et al., 2017). Alternative food sources, and in particular alternative protein sources (plant-based or from seafood), 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 – in particular red meat – has a high environmental impact with respect to water, pesticide and fertilizer usage, ocean acidification, toxic emissions in the air and land eutrophication (Turner-McGrievy et al., 2016; Williams et al., 2006; Niggli et al., 2009; Tilman et al., 2001; Topping et al., 2020; Baroni et al., 2014).

As outlined in the nutritional discussion in Section 5.2, our study investigates solely the carbon footprint with respect to protein content and does not account for other nutritional aspects. Beyond micronutrient targets, and as highlighted by a number of studies, many other factors come into play. For example when comparing protein rich

Table 8
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.

Carbon intensity for dairy products		
Dairy product	Carbon footprint range ($g\ CO_2$ eq./100 g edible) [Min – $Median_{min}$-$Median_{max}$ – Max] $C_{min} - C_{m,min}$ - $C_{m,max} - C_{max}$	List of meta-analysis used, with carbon footprint data ($g\ CO_2$ eq./100 g edible) (**bold font** corresponds to retained data for carbon footprint range)
Cheese (Cow)	533 – 855-1860 – 5880	1347 (Hamerschlag and Venkat, 2011) (*single LCA, USA, average methods*); **855** (**533**-1635)[a] (Clune et al., 2017) (*meta-analysis*); **1860** (1020-**5880**)[b] (Poore and Nemecek, 2018) (*meta-analysis*)
Yogurt (Cow)	117 – 131-288 – 374	217 (Hamerschlag and Venkat, 2011) (*single LCA, USA, average methods*); **131** (**117**-200)[a] (Clune et al., 2017) (*meta-analysis*); **288** ± **30%**(Colomb et al., 2015) (*Average, national agency, France*)
Milk (Cow)	54 – 122-280 – 1710	129 (**54**-750)[a] (Clune et al., 2017) (*systematic review*); 270 (150-700)[b] (Poore and Nemecek, 2018) (*meta-analysis*); **122** ± 30% (Colomb et al., 2015) (*Average, national agency, France*; 106-123 (Williams et al., 2006) (*Table 59, LCA non-organic vs organic, Average, England and Wales*); **280** (130-**1710**)[c] (Opio et al., 2013) (*world average emissions, FAO*)
Eggs (chicken)	130 – 241-420 – 850	483 (Hamerschlag and Venkat, 2011) (*single LCA, USA, average methods*); 346 (**130**-600)[a] (Clune et al., 2017) (*meta-analysis*); **420** (290-**850**)[b] (Poore and Nemecek, 2018) (*meta-analysis*); **241** (Colomb et al., 2015) (*Average, national agency, France*); 525-700 (Williams et al., 2006) (*Table 58, 100% cage non-organic vs organic, egg weight 50 g, Average, England and Wales*);
Milk (Sheep)	160 – 209-840 – 1420	**840** (**160**-**1420**)[c] (Opio et al., 2013) (*world average emissions, FAO*); 320 (200-520)[d] (Batalla et al., 2015) (*12 farms, variation of footprint corresponds to varying yields in different farms, cradle to farm-gate LCA*); **209** (Colomb et al., 2015) (*Average, national agency, France*)
Milk (Goat)	81 – 131-520 – 1420	104-140 (Gutiérrez-Peña et al., 2019) (*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*); 267 (112-505)[d] (Zucali et al., 2020) (*17 farms, variation of footprint corresponds to varying yields in different farms, cradle to farm-gate LCA*); **520** (160-**1420**)[c] (Opio et al., 2013) (*world average emissions, FAO*) 89 (**81**-103)[d] (Robertson et al., 2015) (*5 farms, variation of footprint corresponds to varying yields in different farms, cradle to farm-gate LCA*); **131** (Colomb et al., 2015) (*Average, national agency, France*)
Milk (Buffalo)	260 – 340 - NA – 660	**340** (**260**-**660**)[c] (Opio et al., 2013) (*world average emissions, FAO*); 360-375 (287 - 520)[d] (Pirlo et al., 2014) (*6 farms, cradle to farm-gate LCA*);

[a]Numbers reported here correspond to: median (min–max) as given in Clune et al. (2017).
[b]Numbers reported here correspond to: median (5th percentile-95th percentile) as given in Poore and Nemecek (2018). Poore and Nemecek (2018) does not provide minimum or maximum values used and hence we choose to use (5th percentile-95th percentile) as good representatives of these values.
[c]Numbers reported here correspond to: average (min–max) where the average is the LCA for the total world production, and the variation of footprint corresponds to varying yields across the world. The LCA is from cradle to retail.
[d]Numbers indicated here correspond to average value (farm min–farm max) as given in adjoining references. When several average values are given they correspond to variability across possible allocation scenarios.

Table 9
Protein based carbon intensity: extreme values.

Protein based carbon intensity: extreme values			
Meat-based/dairy product	C_{min}/P_{max} ($g\ CO_2$ eq./g protein)	C_{max}/P_{min} ($g\ CO_2$ eq./g protein)	Geometric average carbon intensity[a] ($g\ CO_2$ eq./g protein)
Beef	43	1574	194
Lamb	36	369	172
Veal	51	128	84
Milk	14	552	54
Cheese	15	348	51
Pork	14	150	41
Turkey	15	55	32
Yogurt	10	91	27
Eggs	10	72	26
Chicken	4	113	25
Rabbit	17	28	23
Duck	10	44	23

[a]Data reported from Table 1.

Table 10
Protein based carbon intensity for milks: extreme values.

Protein based carbon intensity: extreme values			
Milk product	C_{min}/P_{max} ($g\ CO_2$ eq./g protein)	C_{max}/P_{min} ($g\ CO_2$ eq./g protein)	Geometric average carbon intensity ($g\ CO_2$ eq./g protein)[a]
Cow's	14	552	54
Sheep's	15	290	59
Goat's	21	458	76
Buffalo's	68	174	89

[a]Data reported from Table 2.

Table 11
Protein based carbon intensity of different cheeses (starting from cow's milk, unless otherwise mentioned).

Protein based carbon intensity of different types of cheeses				
Type of cheese	P (g protein/100 g)	C (g CO_2 eq./100 g)	C/P (g CO_2 eq./g protein)	Notes
Yellow cheese low fat	30	993 (Flysjö, 2012)	33	
Grana Padano	29.7	1030 (max with diff. allocations 1690) (Bava et al., 2018)	35 (max 57)	hard cooked, dry matter allocation as central value
Pecorino artisanal	28	1700 (Vagnoni et al., 2017)	61	goat cheese, hard cooked
Emmental	27.9 (Agence nationale de sécurité sanitaire de l'alimentation, 2020)	560 (Colomb et al., 2015)	20	hard cooked
Yellow cheese	26	911 (Flysjö, 2012)	35	
Dutch Cheese	25.2	850 (Va. Middelaar et al., 2011)	34	semi-hard
Hushallsost	25 (Anon, 2020l)	873 (Berlin, 2002)	35	
Gouda	25 (S.R.L.R.V.C.A., 2019)	867 (Broekema and Kramer, 2014)	35	
Cheddar	24.8	700 (range with diff. allocations 460-1300) (Aguirre-Villegas et al., 2012)	28 (19–52)	Semi-hard, economic allocation as central value
Cheddar	24.8	860 (range with diff. allocations 590-1220) (Kim et al., 2013)	35 (24–49)	Semi-hard, economic allocation as central value
Cheese (generic)	24	530 (Vergé et al., 2013)	22	canadian meta-analysis
Mozzarella	23.7 (F.C.F.F.V.C.D., 2019)	730 (range with diff. allocations 510-990) (Kim et al., 2013)	31 (22-42)	semi-hard, protein content may vary significantly
San Simon da Costa	23.3 (Anon, 2020m)	1044 (González-García et al., 2013)	45	
Casin (hard) artisanal	23 (Anon, 2020n)	1020 (Canellada et al., 2018)	44	
Pecorino (industrial)	22	1700 (Vagnoni et al., 2017)	77	goat cheese, hard cooked
Camembert	20.7 (Agence nationale de sécurité sanitaire de l'alimentation, 2020)	428 (Colomb et al., 2015)	21	
Soft cheese	20	776 (Doublet et al., 2013)	39	meta-analysis
Franxon (artisanal)	20 (Anon, 2020o)	1020 (Canellada et al., 2018)	51	semi-hard
Gorgonzola	19	600 (max with diff. allocations 1070) (Bava et al., 2017)	32 (max 56)	hard cooked, dry matter allocation as central value
Cheese	19	640 (Flysjö et al., 2014)	34	semi-hard to hard, meta-analysis
Fresh cheese	18 (Doublet et al., 2013)	324	18	meta-analysis
White cheese	18	833 (Flysjö, 2012)	46	
Mould cheese	17	846 (Flysjö, 2012)	50	
Cottage cheese	14	324 (Vergé et al., 2013)	18	canadian meta-analysis
Cottage cheese	12	370 (Flysjö, 2012)	31	
Cream cheese	10	692 (Flysjö, 2012)	69	
Cream cheese low fat	7.8	447 (Flysjö, 2012)	57	

foods it has been noted that not all protein sources are equivalent because some are easier to digest (Berardy et al., 2019; Consultation, 2011). Furthermore, factors such as very local dependencies of carbon footprint (from one region of a country to another) (Vázquez-Rowe et al., 2017), economic cost of the alternative diet (Perignon et al., 2016; Vázquez-Rowe et al., 2017) and cultural adequacy (Perignon et al., 2016) 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 mitigate climate change.

Table 12
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/100 g)	C (g CO_2 eq./100 g)	C/P (g CO_2 eq./g protein)	Notes
Yogurt	4.4	150 (Vergé et al., 2013)	34	canadian meta-analysis
Yogurt low fat	3.9	133 (Flysjö, 2012)	34	
Yogurt	3.4	152 (Flysjö, 2012)	45	
Yogurt	3.3	335 (Doublet et al., 2013)	102	meta-analysis
Whey protein concentrate (special)	90	1736 (Flysjö, 2012)	19.3	
Whey protein concentrate	80	1640 (Flysjö, 2012)	20.5	
Whey powder	30	1010 (Vergé et al., 2013)	34	canadian meta-analysis
Whey powder	25	740 (Flysjö et al., 2014)	30	meta-analysis

Table 13
Carbon footprint and protein intake from meat and dairy for a reference **American** diet, and alternative diets. Product consumptions are all given in g/person/day.

Product	Reference	Vegetarian	Low CO_2	Chicken
Pork	63.0 (O. for Economic Co-operation and D. (OECD), 2020)	0	0	0
Chicken	136.2 (O. for Economic Co-operation and D. (OECD), 2020)	0	315.6	382.9
Beef	71.5 (O. for Economic Co-operation and D. (OECD), 2020)	0	0	0
Lamb	1.4 (O. for Economic Co-operation and D. (OECD), 2020)	0	0	0
Milk	181.4 (Anon, 2020c)	587.7	0	0
Cheese	49.7 (Anon, 2020c)	161.1	0	0
Yogurt	16.6 (Anon, 2020c)	53.9	38.6	0
Eggs	39.3 (Anon, 2020d)	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 footprint[b]	**1 973**	**1 324**	**736**	**731**
relative decrease	100%	67%	37%	37%
Carbon footprint[c]	**1 321**	**1 008**	**528**	**433**
relative decrease	100%	76%	40%	33%

[a]Calculated, g/day.
[b]Calculated with world average, kg CO_2 eq./year.
[c]Calculated with North America data, kg CO_2 eq./year.

Table 14
Carbon footprint and protein intake from meat and dairy for a reference **Chinese** diet, and alternative diets. Product consumptions are all given in g/person/day.

Product	Reference	Vegetarian	Low CO_2	Chicken
Pork	83.3 (O. for Economic Co-operation and D. (OECD), 2020)	0	0	0
Chicken	31.8 (O. for Economic Co-operation and D. (OECD), 2020)	0	75.8	171.3
Beef	10.4 (O. for Economic Co-operation and D. (OECD), 2020)	0	0	0
Lamb	8.5 (O. for Economic Co-operation and D. (OECD), 2020)	0	0	0
Milk	39.2 (Anon, 2020e)	144.2	0	0
Cheese	0.1 (Anon, 2020e)	0.2	0	0
Yogurt	9.4 (Anon, 2020e)	34.6	22.4	0
Eggs	62.7 (Anon, 2020f)	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 footprint[b]	**663**	**391**	**334**	**327**
relative decrease	100%	59%	50%	49%
Carbon footprint[c]	**675**	**419**	**408**	**463**
relative decrease	100%	62%	60%	69%

[a]Calculated, g/day.
[b]Calculated with world average, kg CO_2 eq./year.
[c]Calculated with Asia data, kg CO_2 eq./year.

CRediT authorship contribution statement

R. Gaillac: Conceptualization, Methodology, Data analysis, Writing – review & editing. **S. Marbach:** Conceptualization, Methodology, Data analysis, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Protein content of meat and dairy retained for this study

Table 15
Carbon footprint and protein intake from meat and dairy for a reference **Brazilian** diet, and alternative diets. Product consumptions are all given in g/person/day.

Product	Reference	Vegetarian	Low CO_2	Chicken
Pork	63.0 (O. for Economic Co-operation and D. (OECD), 2020)	0	0	0
Chicken	110.4 (O. for Economic Co-operation and D. (OECD), 2020)	0	255.6	302.2
Beef	69.0 (O. for Economic Co-operation and D. (OECD), 2020)	0	0	0
Lamb	1.4 (O. for Economic Co-operation and D. (OECD), 2020)	0	0	0
Milk	132.1 (Anon, 2020g)	610.5	0	0
Cheese	19.7 (Anon, 2020g)	91.2	0	0
Yogurt	21.2 (Anon, 2020g)	97.9	49.0	0
Eggs	21.3 (Anon, 2020b)	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 footprint[b]	**1696**	**1015**	**580**	**577**
relative decrease	100%	60%	34%	34%
Carbon footprint[c]	**1 516**	**1007**	**442**	**408**
relative decrease	100%	66%	29%	27%

[a]Calculated, g/day.
[b]Calculated with world average, kg CO_2 eq./year.
[c]Calculated with South America data, kg CO_2 eq./year.

Table 16
Carbon footprint and protein intake from meat and dairy for a reference **Australian** diet, and alternative diets. Product consumptions are all given in g/person/day.

Product	Reference	Vegetarian	Low CO_2	Chicken
Pork	58.6 (O. for Economic Co-operation and D. (OECD), 2020)	0	0	0
Chicken	116.2 (O. for Economic Co-operation and D. (OECD), 2020)	0	301.4	359.5
Beef	54.8 (O. for Economic Co-operation and D. (OECD), 2020)	0	0	0
Lamb	19.2 (O. for Economic Co-operation and D. (OECD), 2020)	0	0	0
Milk	275.9 (Anon, 2021)	885.6	0	0
Cheese	37.3 (Anon, 2021)	119.6	0	0
Yogurt	24.7 (Anon, 2021)	79.2	64.0	0
Eggs	22.9 (Anon, 2020b)	73.4	59.4	0
Diet factor	1	3.2	2.6	3.1
Total protein[a]	75.6	75.6	75.6	75.6
Carbon footprint[b]	**1 859**	**1 289**	**690**	**687**
relative decrease	100%	69%	37%	37%
Carbon footprint[c]	**1 165**	**828**	**490**	**512**
relative decrease	100%	71%	42%	44%

[a]Calculated, g/day.
[b]Calculated with world average, kg CO_2 eq./year.
[c]Calculated with Oceania data, kg CO_2 eq./year.

Table 17
Carbon footprint and protein intake from meat and dairy for a reference **Indian** diet, and alternative diets. Product consumptions are all given in g/person/day.

Product	Reference	Vegetarian	Low CO_2	Chicken
Pork	0.5 (O. for Economic Co-operation and D. (OECD), 2020)	0	0	0
Chicken	6.6 (O. for Economic Co-operation and D. (OECD), 2020)	0	21.6	46.1
Beef	1.4 (O. for Economic Co-operation and D. (OECD), 2020)	0	0	0
Lamb	1.4 (O. for Economic Co-operation and D. (OECD), 2020)	0	0	0
Milk	129.9 (Anon, 2020g)	162.9	0	0
Cheese	6.6 (Anon, 2020g)	8.2	0	0
Yogurt	6.3 (Anon, 2020h)	7.9	20.7	0
Eggs	8.9 (Anon, 2020b)	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 footprint[b]	**184**	**166**	**90**	**88**
relative decrease	100%	90%	49%	48%
Carbon footprint[c]	**200**	**179**	**110**	**125**
relative decrease	100%	90%	55%	63%

[a]Calculated, g/day.
[b]Calculated with world average, kg CO_2 eq./year.
[c]Calculated with Asia data, kg CO_2 eq./year.

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 originally contained in proteins in the food (purple circle in the amino acids of Fig. 2) (Agency, 2002). The conversion factor most widely used today, in particular used to calculate the data retained in this study, relies on Jones (1941a). 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 (Jones, 1941b) and a slightly different factor is strongly recommended by scientists today (Mariotti et al., 2008). 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 importantly does not vary much among the food categories investigated.

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 (Agency, 2002; F.C.F.F.V.C.D., 2019; S.R.L.R.V.C.A., 2019; Agence nationale de sécurité sanitaire de l'alimentation, 2020). Protein content of common meat-based products may be found in Table 5 and of dairy products in Table 6. In each table, the protein content range is the minimum to maximum of protein content that we have retained.

Appendix B. Carbon footprint of meat and dairy retained for this study

We report here values of carbon footprint for the production per gram of meat and dairy products from various sources. Carbon footprint per 100 g of edible food of common meat-based products is given in Table 7 and of dairy products in Table 8. In each table, we highlight the carbon footprint range that we have retained.

Appendix C. Calculating carbon footprint per g of protein

We present in Tables 9 and 10 extreme values of carbon footprint per g of protein as calculated using the extreme retained values of carbon footprint in Table 7 and of dairy products in Table 8.

Appendix D. Carbon footprint per g of protein of different type of cheeses

We present in Table 11 the protein based carbon intensity of different cheeses and in Table 12 of more varied dairy products.

Appendix E. Typical dietary intakes and comparison of carbon footprint of different diets equivalent in protein

We present in Tables 13–17 the carbon footprint and protein intake from meat and dairy consumption for reference and alternative diets for various countries.

Appendix F. An online tool to guide dietary choices

We detail here the methods used to calculate an individuals carbon footprint based on meat and dairy consumption (accessible at http://www.sciriousgecko.com/ArticleMeat.html). Based on input data of weekly consumption, the tool returns the total carbon footprint of the products (based on world averaged carbon footprints $C^{\text{world}}_{\text{m,product}}$), comparing it to the average European Union (E.U.) value (based on world averages) – see Section 4. It also gives the corresponding daily protein intake, comparing it to the E.U. average value. Fig. 8 shows an example close to the typical E.U. diet.

The data used to compute the carbon footprint and protein intake is taken from Tables 5–8 with a methodology similar to the one detailed in Section 5. To compare to the average E.U. data, we must take into account food losses. In fact, average E.U. 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. in Shepon et al. (2018). Note that food losses especially for meat can be much higher (up to 96% for beef). The source code is freely available on the website (Anon, 0000). Future releases including geographical origin and type of farming are the object of future work.

Appendix G. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.128766.

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